# Intro to Meteors and the NASA All-Sky Camera Network

## - The Fireball Project -


Meteoroid Environment Office
NASA Marshall Space Flight Center

# Who are we?
# Meteoroid Environment Office (MEO)

- Established by the Office of Safety and Mission Assurance in late 2004.
- Responsible for meteoroid environments pertaining to spacecraft engineering and operations.
- Located at the NASA Marshall Space Flight Center in Huntsville, Alabama.

# Outline

A. Background
   I. Terminology – meteors, comets, asteroids, etc
   II. Motivation – why do we study this?
   III. Methods – how do we study meteors?
B. All-Sky Cameras
   I. System Components
   II. Website
   III. Case Study: Grimsby
C. Use in the Classroom

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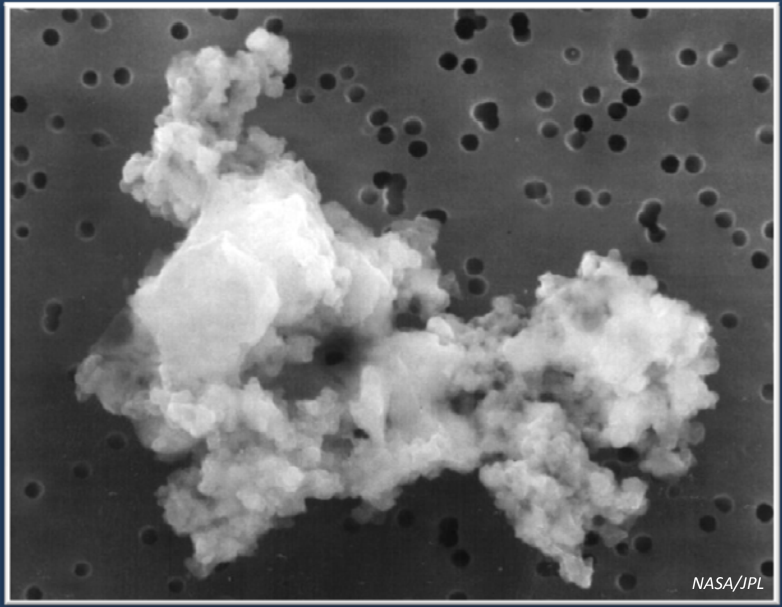
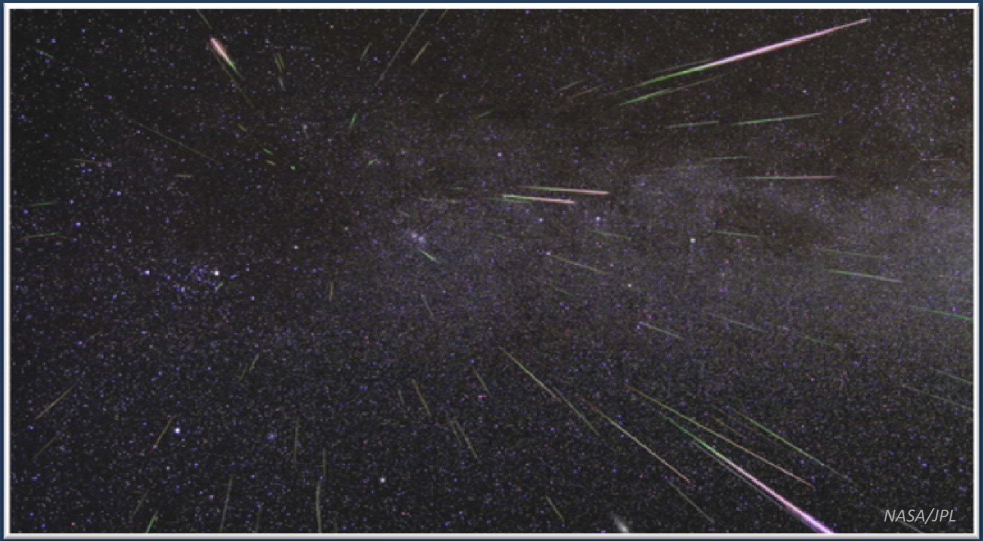
# Confusing Terms?

# Meteoroids, Meteors, and Meteorites?

***Meteoroids*** are chunks of rock and ice out in space. They are about the size of a boulder or smaller. They aren't quite big enough to be an asteroid.


NASA/JPL

***Meteors*** are the streaks of light that you see as a meteoroid *ablates*, or burns up, in the Earth's atmosphere – commonly called a 'shooting star' or 'falling star'.

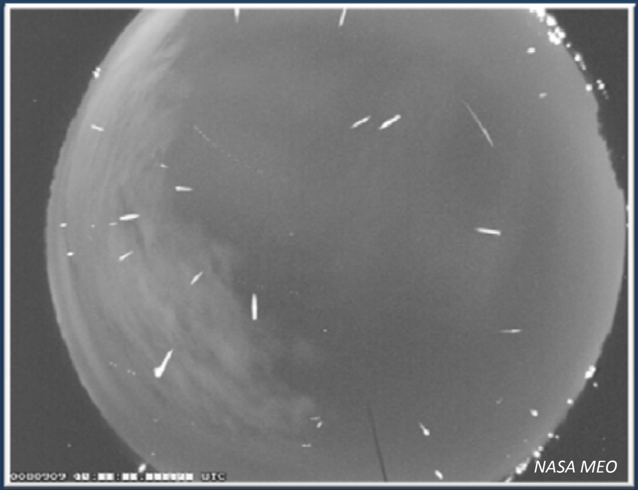


# Ablation/Ionization

Why do we see a trail of light?

- When the meteoroid comes in contact with molecules in the atmosphere, electrons pop off – ionization – some energy is released as light.
- The meteors are usually completely ablated -‘burned up’ - by 40 miles up, though our perception is that they have fallen down ‘right over the next hill’

A ***fireball*** is a bright meteor. Its peak magnitude is brighter than Venus.




Fireballs

A ***superbolide*** is a very bright meteor. Its peak magnitude is brighter than the full Moon.


Superbolide

*Meteorites* are what is left of the meteor if it hits the surface of the Earth.

## Features of meteorites

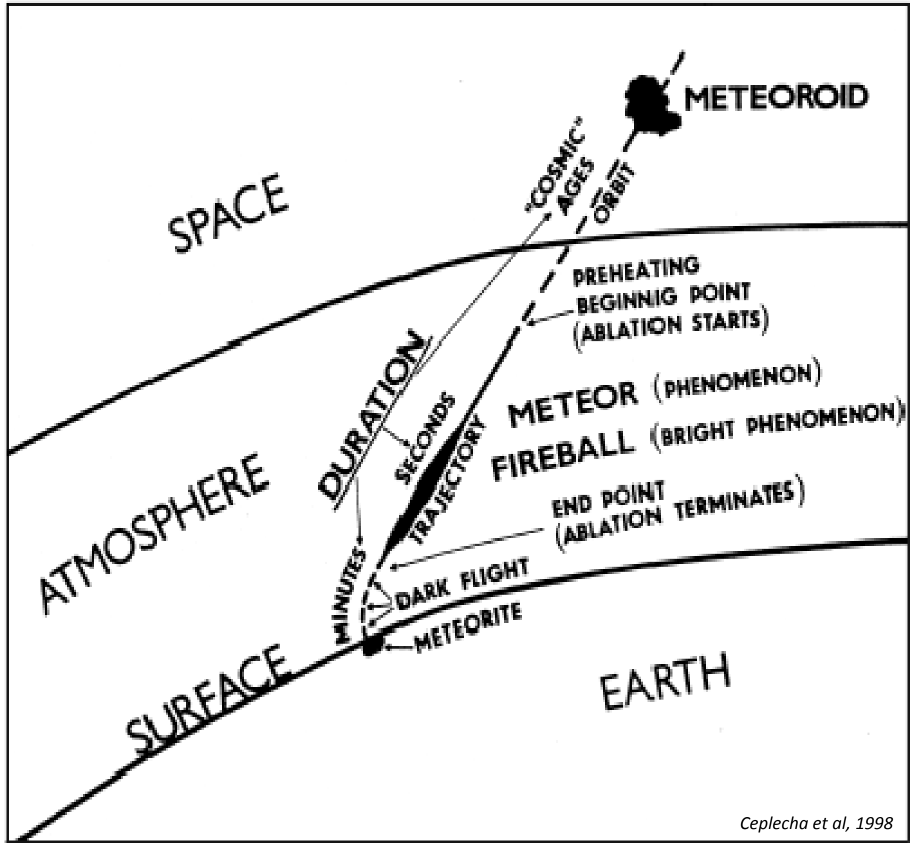
- Mostly heavier than a normal Earth rock
- Fusion crust (black or brown)
- Magnetic (metallic iron in Earth rocks have usually decayed)
  - Not a sure-fire way to tell – some Earth rocks are magnetic too
  - File down outside – will find specks of metal

Allende meteorite fragment


Grimsby meteorite fragment

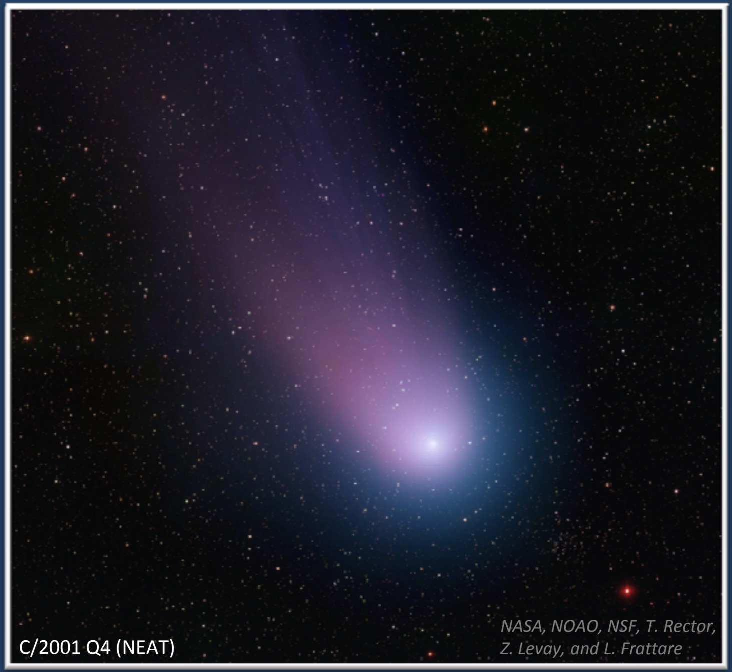
# Recap

- Meteoroid
- Meteor
- Meteorite



Ceplecha et al, 1998

# Sources of Meteoroids

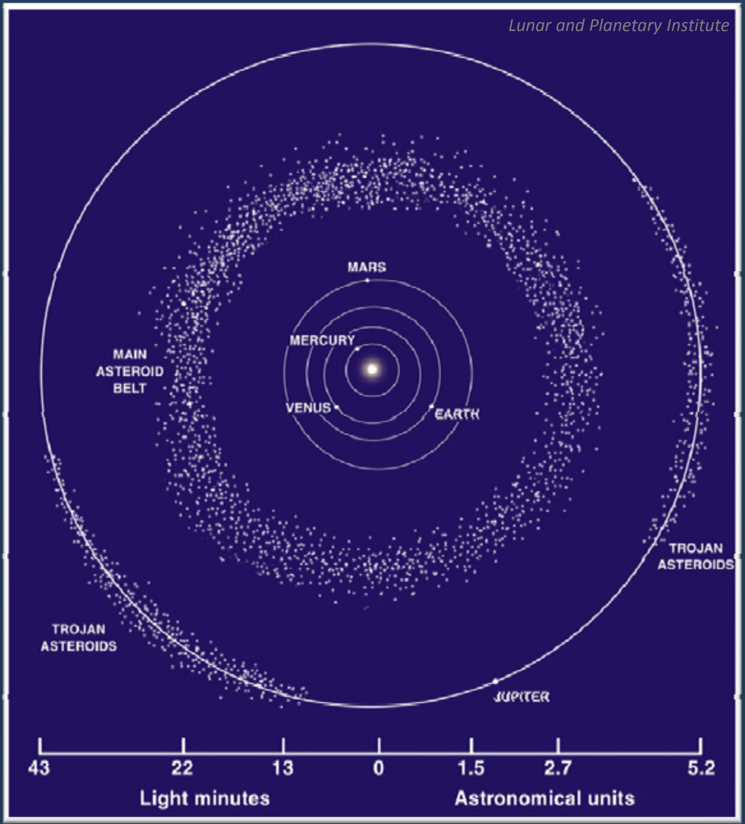

Asteroids

Comets

(Meteoroids can also come from the Moon or other planets, but this is VERY rare.)

# Asteroids

- Asteroids: Greek for “star-like”
  - The first asteroid, 1 Ceres, was found in 1801
- Made of rocky material and other elements
  - Many contain carbon
  - Some are rich in iron and nickel
- They range in size, from a boulder to several hundreds of kilometers across
- Primarily found in the Asteroid belt, between Mars and Jupiter, but also
  - Trojans in Jupiter’s orbit
  - Near-Earth asteroids
- Asteroid collisions can lead to meteoroids




Asteroid locations

# Comets

- Aristotle derived the word komētēs, meaning "stars with hair"
  - Comets were thought to be unlucky, or even interpreted as attacks from heavenly beings
- An asteroid-like object, but made up of ice, dust, and rock, like a 'dirty snowball'
- When close to the Sun they exhibit a coma (fuzzy temporary atmosphere) and/or a tail because the Sun heats up the comet
  - The tail always points away from the Sun
- Sizes between 1 and 20 kilometers across (not including tail or coma)
- Most meteoroids come from comets

Comet with tail

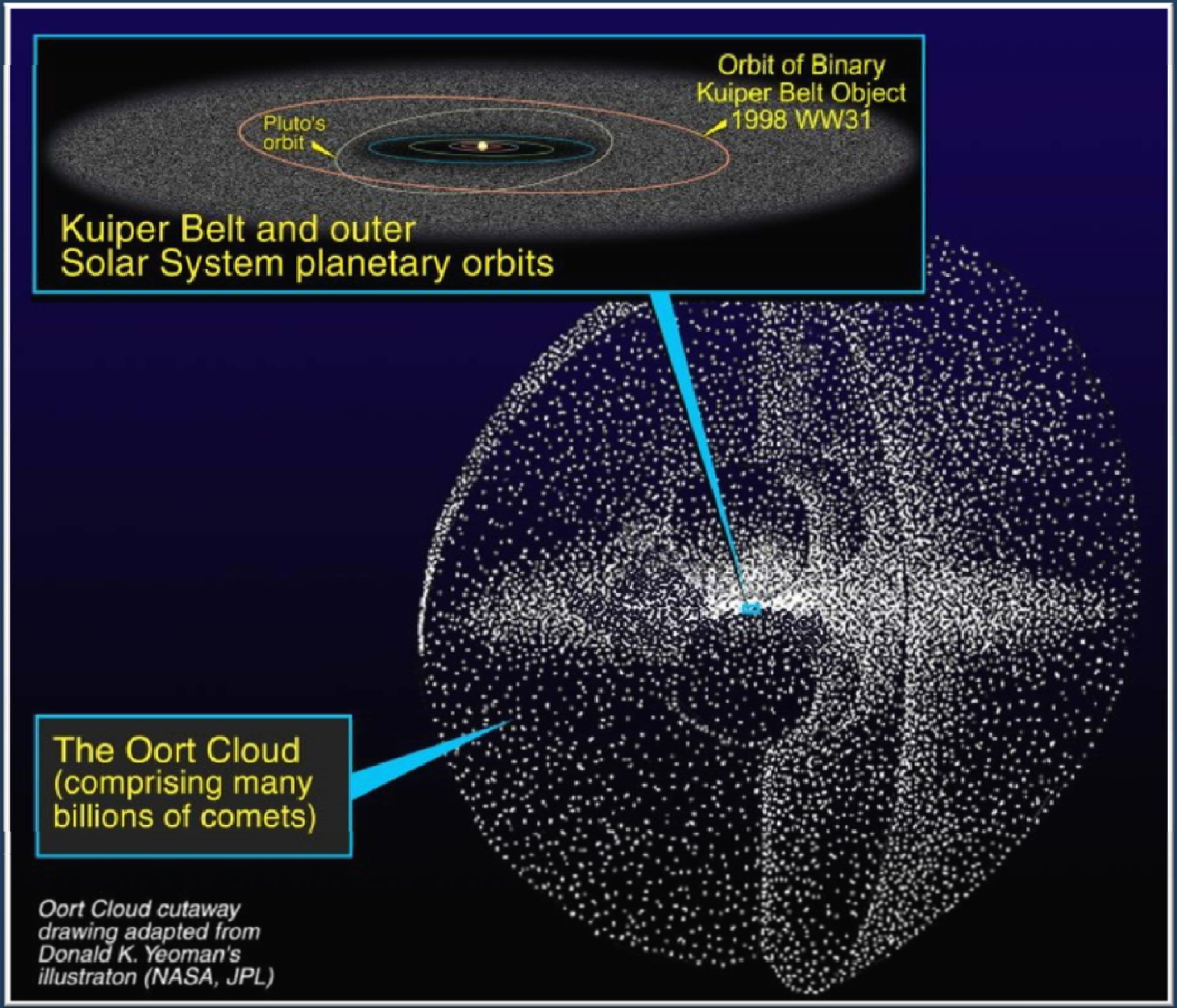


Comet with coma

# Sources of Comets

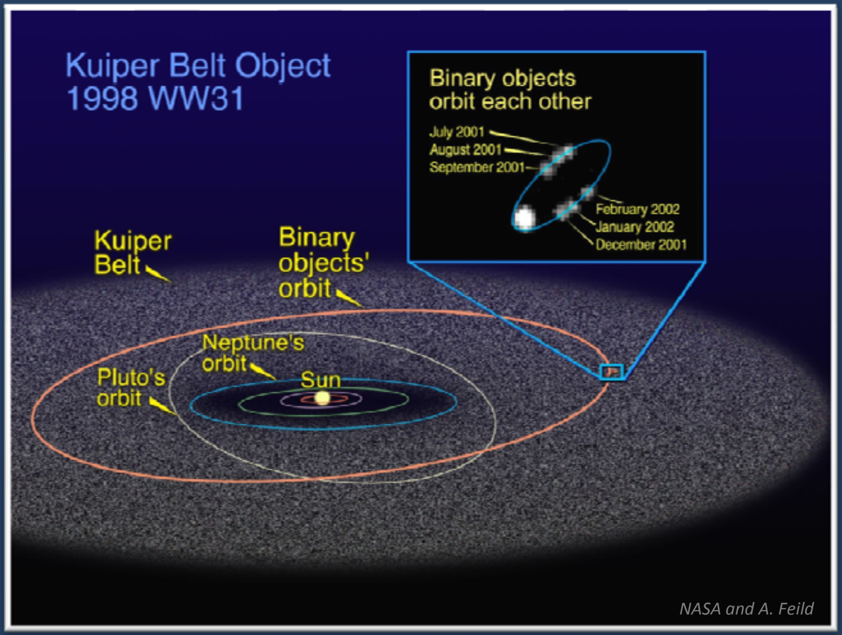
Kuiper Belt

Oort Cloud



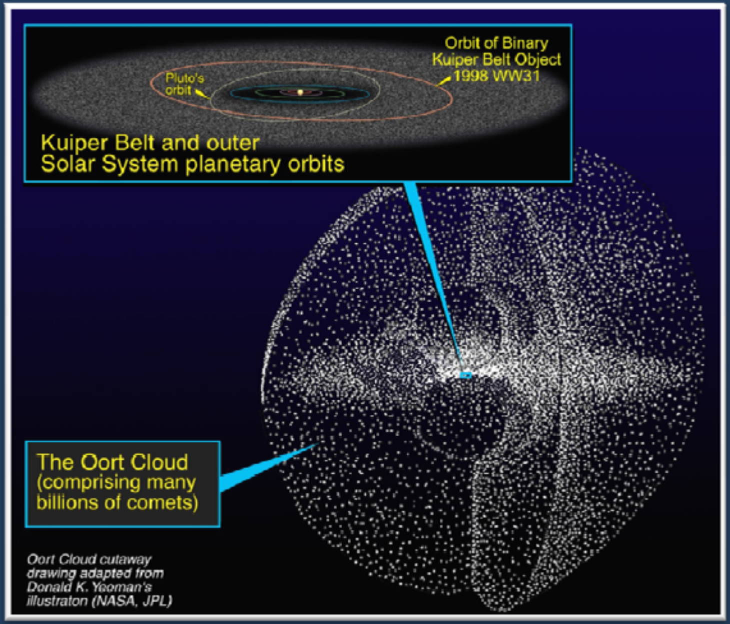
# Kuiper Belt

- “Belt” of small, icy bodies starting beyond Neptune
- Holds approx 100 million objects
- Objects can be disturbed, often by gravity of planets, then shot into a different orbit



# Oort Cloud

- “Cloud” of icy bodies outside the solar system
- Several trillion objects 1 km and larger
- Objects can be disturbed by gravity of passing stars and the Milky Way itself

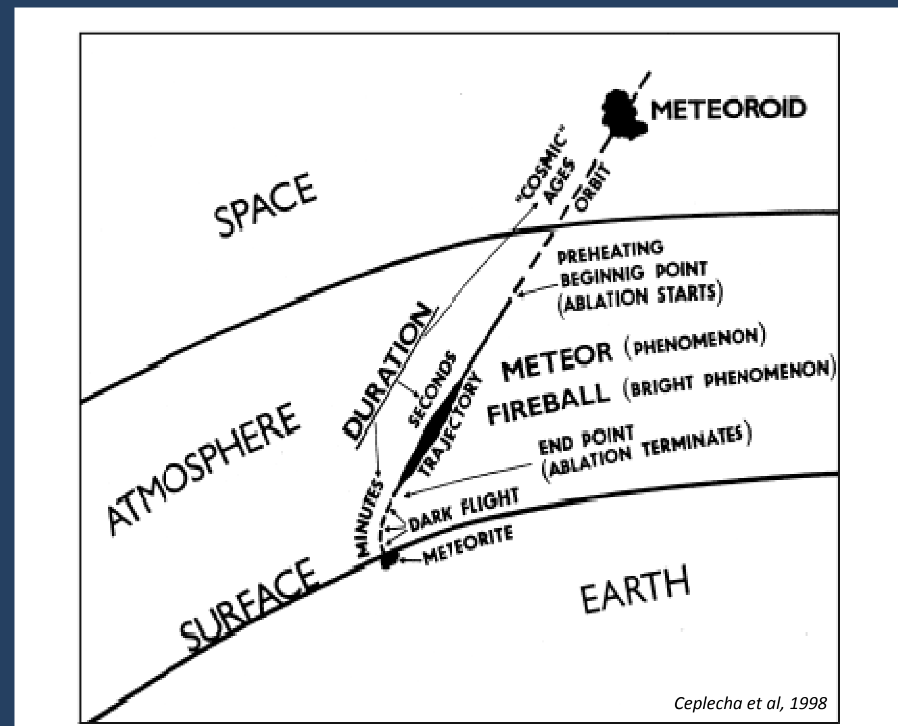


Oort Cloud (Comets)
Kuiper Belt (Comets)
Asteroid Belt (Asteroids)

Meteoroid

Meteor

Meteorite

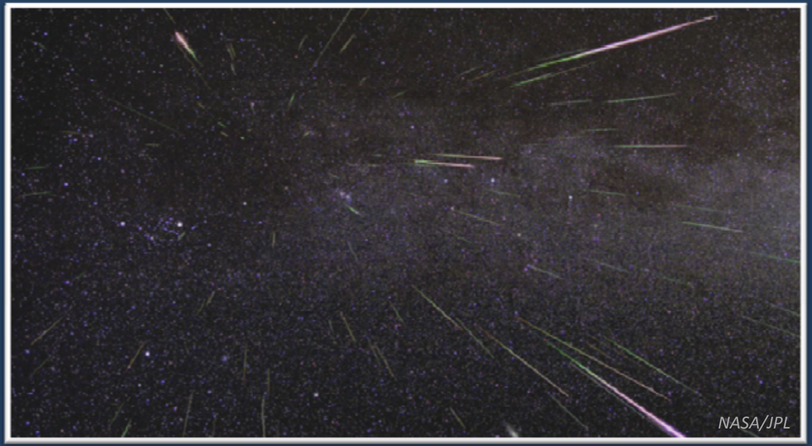


*Ceplecha et al, 1998*

The All-sky Cameras detect *meteors*

# 2 Main Categories of Meteors

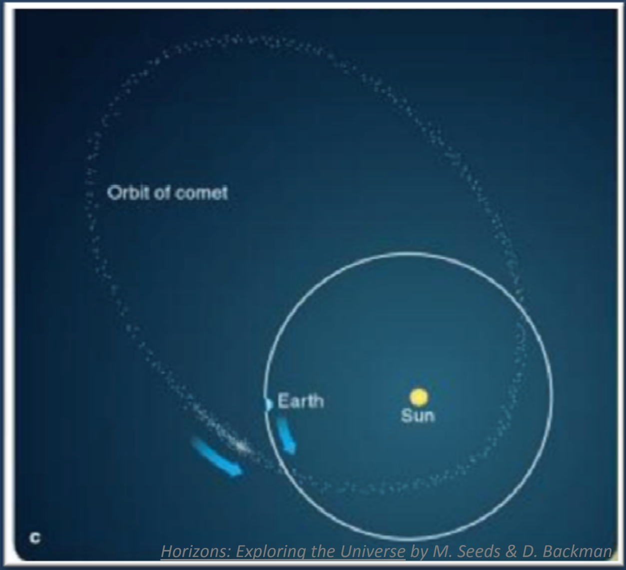
Shower




Sporadic aka
"Background"

# Shower Meteors

- Meteors associated with a particular comet (or asteroid, in the case of the Geminids)
- Caused by Earth passing through dust trails left by comets in their orbits
- Observed specific times during the year
- Rates (number of meteors per hour) are variable, they differ shower to shower and year to year



Horizons: Exploring the Universe by M. Seeds & D. Backman

# Shower Meteors

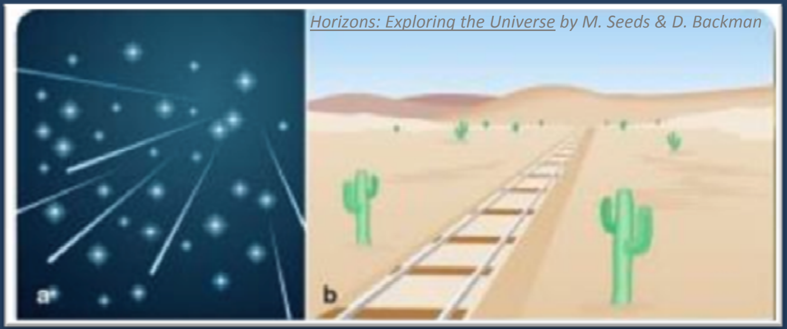
All meteors associated with one particular shower have similar orbits, and they all <u>appear</u> to come from the same place in the sky (called the *radiant)*.

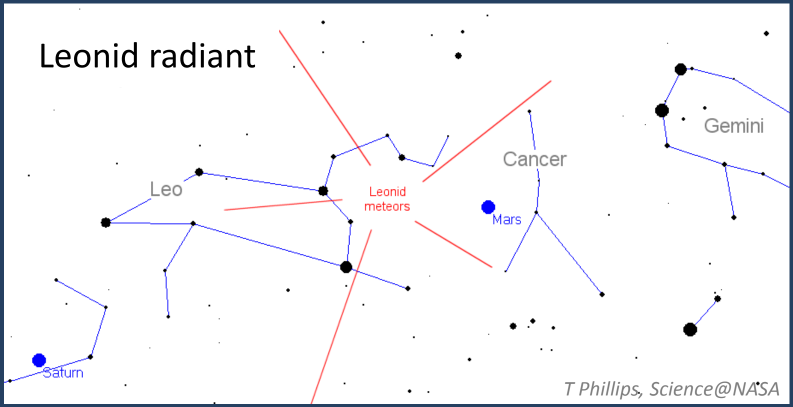
Meteor showers are named based on their radiant location. Examples:

- The Leonids have a radiant located in the constellation Leo
- The radiant of the Draconid meteor shower is in Draco

Shower meteors enter Earth's atmosphere along parallel paths

Perspective makes shower meteors appear to come from a single point in the sky, just like parallel railroad tracks appear to diverge from a point on the horizon



# Annual Meteor Showers

| Shower (3 letter code) | Activity | Peak | Radiant | | ZHR |
|---|---|---|---|---|---|
| | | | α | δ | (meteors/hr) |
| Quadrantids (QUA) | Dec 28 - Jan 12 | Jan 04 | 230° | +49° | 120 |
| Lyrids (LYR) | Apr 16 - Apr 25 | Apr 22 | 271° | +34° | 18 |
| η-Aquariids (ETA) | Apr 19 - May 28 | May 06 | 338° | -01° | 70* |
| June Bootids (JBO) | Jun 22 - Jul 02 | Jun 27 | 224° | +48° | Var |
| South. δ-Aquariids (SDA) | Jul 12 - Aug 23 | Jul 30 | 340° | -16° | 16 |
| α-Capricornids (CAP) | Jul 03 - Aug 15 | Jul 30 | 307° | -10° | 5 |
| Perseids (PER) | Jul 17 - Aug 24 | Aug 13 | 48° | +58° | 100 |
| Draconids (DRA) | Oct 06 - Oct 10 | Oct 08 | 262° | +54° | Var |
| Southern Taurids (STA) | Sep 10 - Nov 20 | Oct 10 | 32° | +09° | 5 |
| Orionids (ORI) | Oct 02 - Nov 07 | Oct 21 | 95° | +16° | 25* |
| Northern Taurids (NTA) | Oct 20 - Dec 10 | Nov 12 | 58° | +22° | 5 |
| Leonids (LEO) | Nov 06 - Nov 30 | Nov 18 | 152° | +22° | 20+* |
| Monocerotids (MON) | Nov 27 - Dec 17 | Dec 09 | 100° | +08° | 2 |
| σ-Hydrids (HYD) | Dec 03 - Dec 15 | Dec 12 | 127° | +02° | 3 |
| Geminids (GEM) | Dec 07 - Dec 17 | Dec 14 | 112° | +33° | 120 |
| Dec. Leonis Minorids (DLM) | Dec 05 - Feb 04 | Dec 20 | 161° | +30° | 5 |
| Ursids (URS) | Dec 17 - Dec 26 | Dec 23 | 217° | +76° | 10 |

This is a partial list of annual meteor showers. See the lists maintained by the International Meteor Organization at www.imo.net

# Sporadic Background Meteors

- Meteors not associated with a particular comet/meteor shower
- Drifted from their original orbit (from comet or asteroid) over time
- Observed all year round with rates higher just before dawn
- Rates vary slightly during the year, about 8 meteors per hour can be seen on any given evening

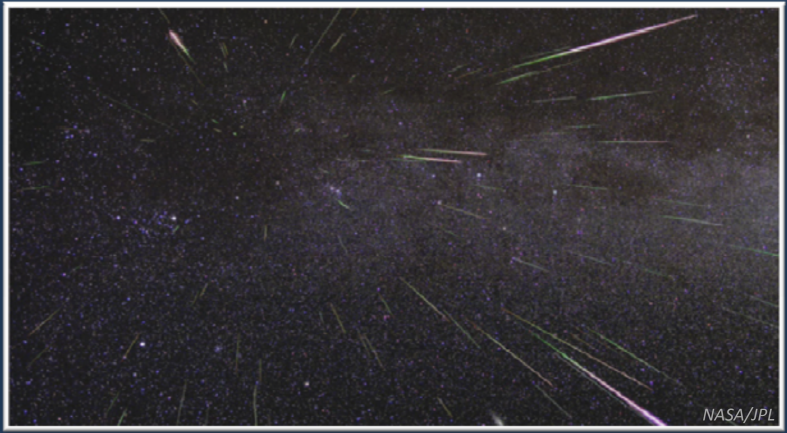
# Sporadic Background Meteors

These background meteors were originally associated with a shower, but over time they have dispersed.

The public knows more about meteor showers as they are more visually spectacular.

Showers often have higher rates and brighter meteors.


Sporadic Background Meteors




Shower Meteors

# What Produces Meteorites?

- Meteoroids from comets are less dense because they contain ices.   These rarely make it to the ground.

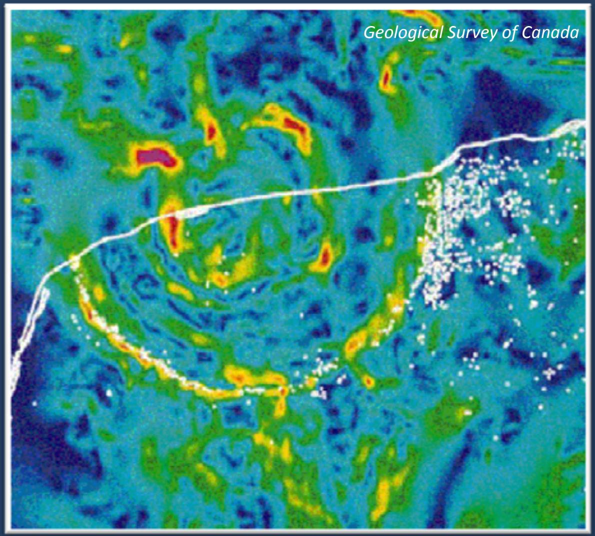
- Meteoroids from asteroids and planets are denser, and can survive traveling through the atmosphere to hit the ground.

- Meteorites rarely hit people, houses, cars, or animals.


Grimsby Meteorite, 2009

# Some Impact Features on Earth


Barringer Crater (AZ)
Crater 1 mile across
Asteroid 150 ft across
Impact estimated to occur 50,000 years ago




Chicxulub (Mexico)
Crater 110 miles across
Asteroid 10 miles across
Impact estimated to occur 65 million years ago

# They don't always leave a crater…

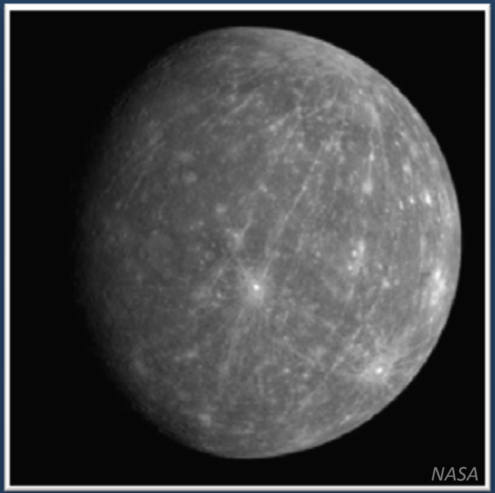
- Tunguska (Russia, 1908) – explosion about 5-10 km above Earth's surface (no crater)

- 1,000 times as powerful as the atomic bomb dropped on Hiroshima, Japan

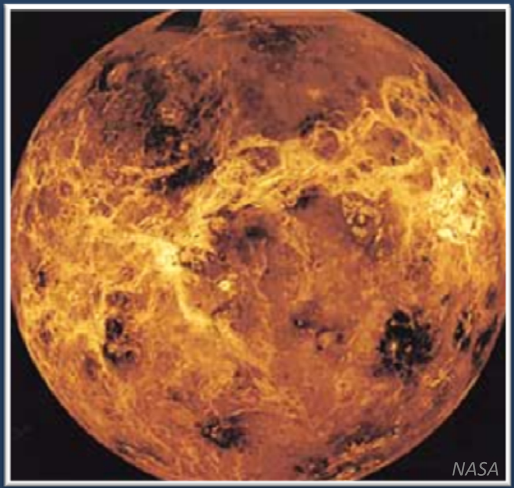
- The explosion knocked over an estimated 80 million trees covering 830 square miles

Leonid Kulik

# Impact Features on Other Bodies

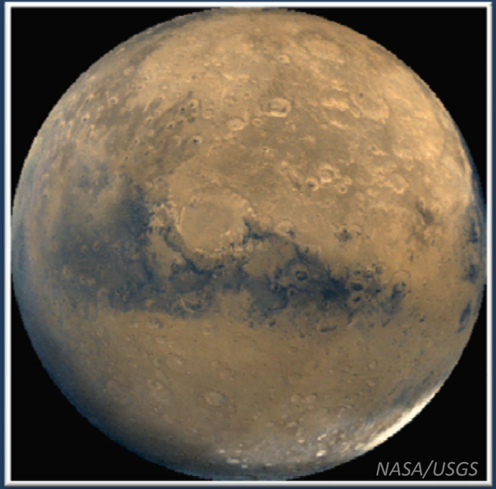



Mercury

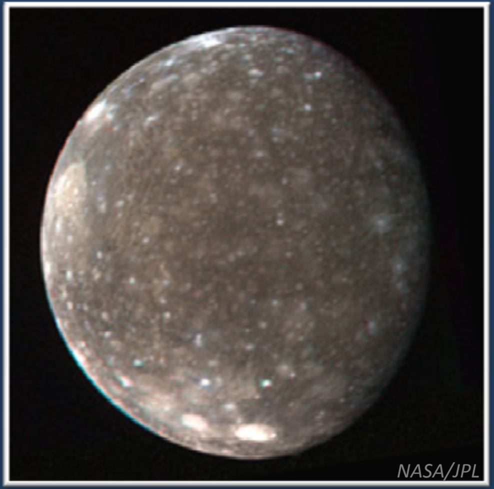



Venus


Moon



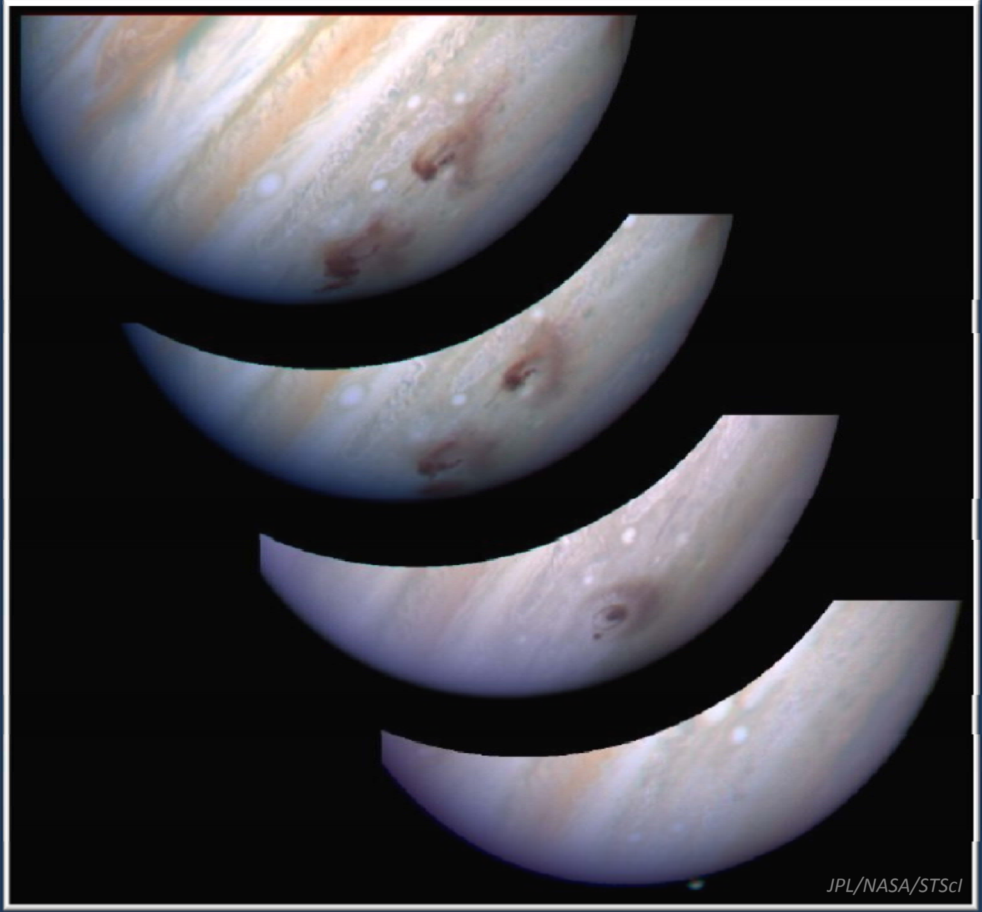

Mars



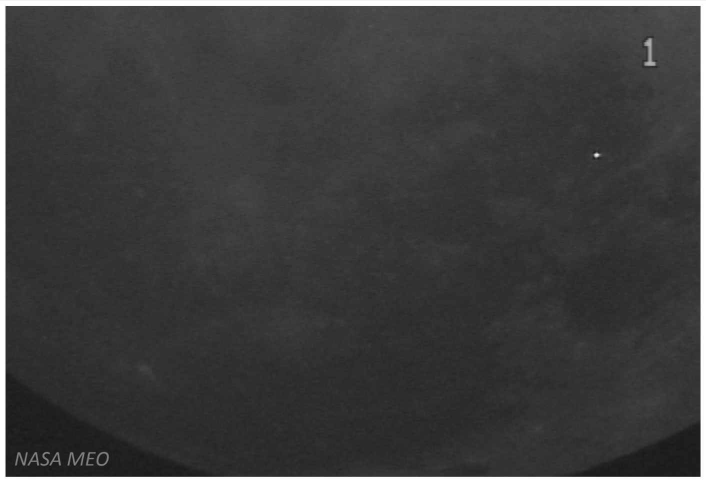

Callisto


Mimas

# Impacts on Other Bodies




Pieces of Shoemaker-Levy 9 impact Jupiter, 1994




Impact flash on the Moon, 2006

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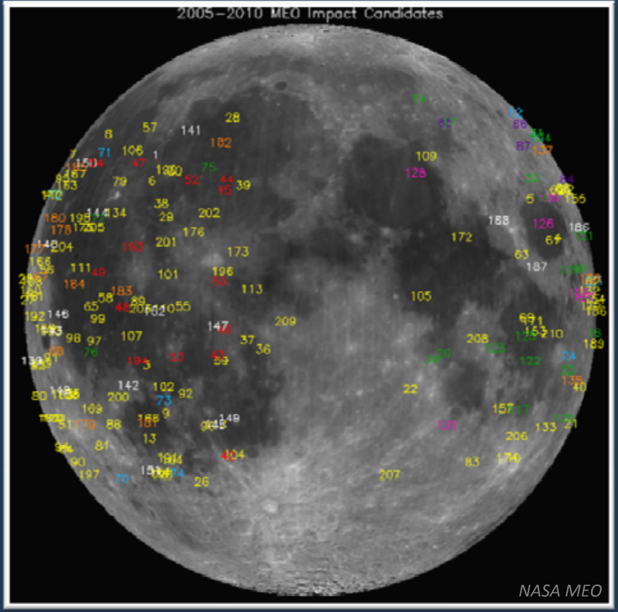
# Why study these bodies?
# - Science -

They give information about the early Solar System (SS)

- Comets come from the SS's farthest and coldest regions, stuff left over from the formation of the SS

Info about large meteoroids impacting planetary bodies (like Mars, the Moon, & Venus)

- Important for dating young planetary surfaces
- Tell us information about the meteoroid environment



# Why study these bodies?
# - Engineering -

Millions of particles hit our atmosphere daily

- International Space Station, the Space Shuttle, and satellites need to be designed to withstand meteoroid impacts


NASA

Data about shower and sporadic background meteors is used to calibrate NASA models.

# Why study these bodies?
# - Planetary Protection -

Asteroids are tracked as they could potentially do large-scale damage on Earth.

# Energy of a meteoroid

A 1-millimeter meteoroid has the punch of a 22-caliber bullet.

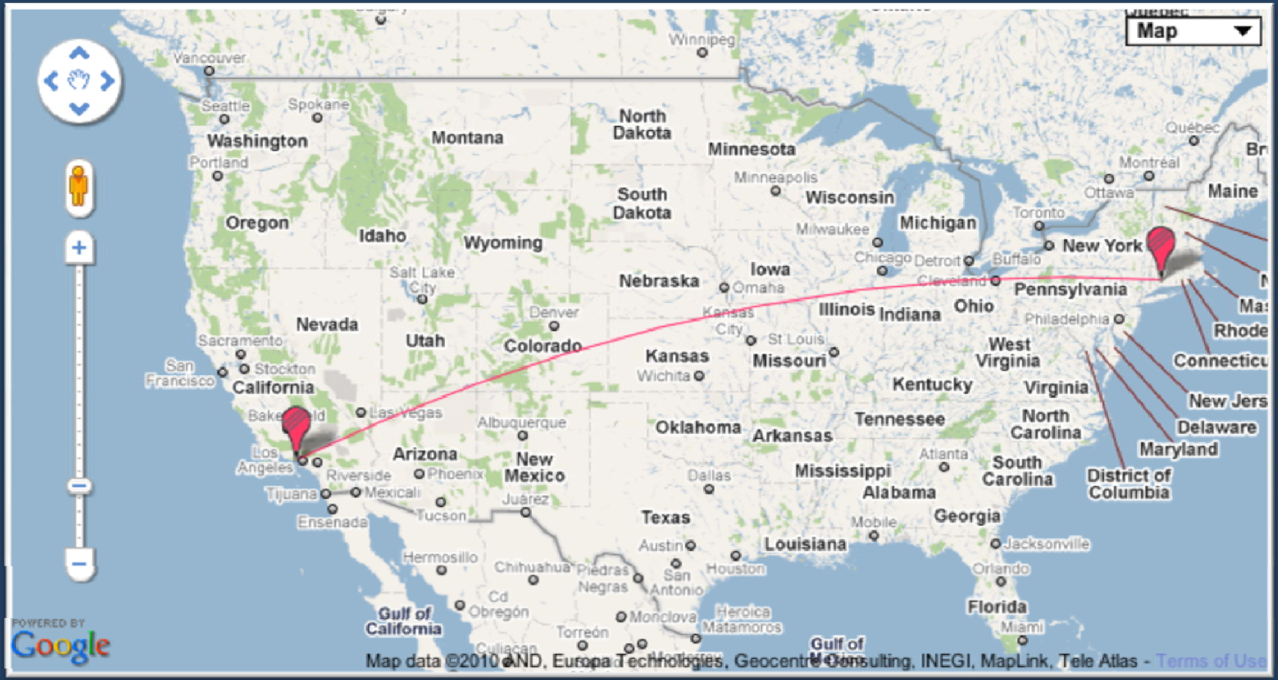
Cm-size meteoroids have the destructive power of cannon shells.

…How can that be?

# They Travel Fast!

Between 11 and 70 km/s

NYC to LA in 1 to 7 minutes



# Collision!

- Earth is protected by its atmosphere
  - 73,000 pounds of meteoroids burn up in Earth's atmosphere every 24 hours
- Satellites/Space Shuttle/International Space Station are completely exposed to these dangers
  - ISS has a 1/100 chance of being penetrated in its 20 year operational lifetime
  - Particles 0.04 cm in size can penetrate spacesuits
- The sporadic background meteoroids account for 90% of spacecraft meteoroid risk

# Laboratory Example


Navy Transit Satellite

(before being shot with a 5 cm aluminum ball moving at 6 km/s = 13,400 mph)

# Laboratory Example


The Aftermath

(after being shot with a 5 cm aluminum ball moving at 6 km/s = 13,400 mph)

# Spacecraft Affected by Meteoroids - Olympus -

What: ESA communication satellite


Event: Struck by a Perseid near the time of the shower peak in August 1993

Outcome: Spacecraft sent tumbling, by the time control restored the onboard fuel had been exhausted, ending the mission

# Spacecraft Affected by Meteoroids - Chandra X-ray Observatory -

What: NASA observatory

Event: Struck by a Leonid or sporadic(?) near the time of Leonid shower peak in November 2003

Outcome: Spacecraft ‘wobbled’, but all systems continued to operate normally following the event

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# Methods of Meteor Detection


Ground-based optical
(visual, photographic, video)


Radar


Acoustic (Infrasound)

# Visual Meteor Detection

- Performed by observers
- Data are rough estimates and what can be recorded is very limited
- Good global coverage
- Observations hampered by Moon & daylight
- Forecasts bias observers

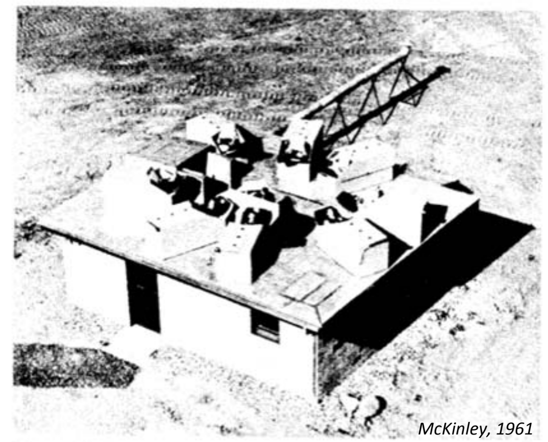



FIG. 3-3. Modern visual meteor observing at Springhill Meteor Observatory near Ottawa. Warm air is supplied to the individual compartments.


Cold winter nights!

# Photographic Meteor Detection

Performed using photographic cameras & intensifiers

- Can amplify light many times to make faint sources detectable.
- Multiple stations plus use of rotating shutter enable location, speed, and orbit determinations

Networks set up around the world in 1950's to 1970's, only one still in existence.

Pros

- Sensitive to faint and bright objects
- High resolution
- Can be automated to *some* degree
- Large fields of view

UWO

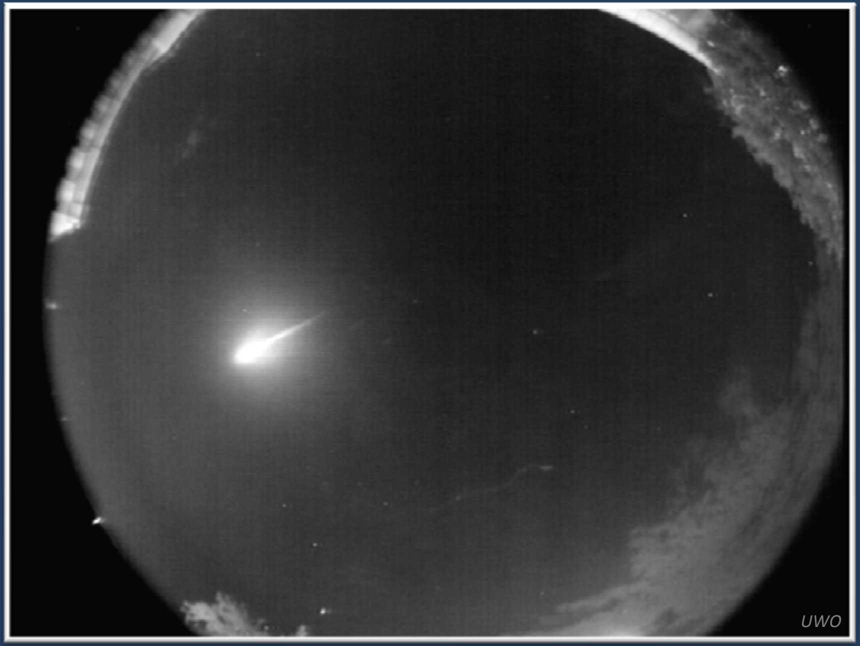

Halliday, 1971

MORP

# Video Meteor Detection

Pros

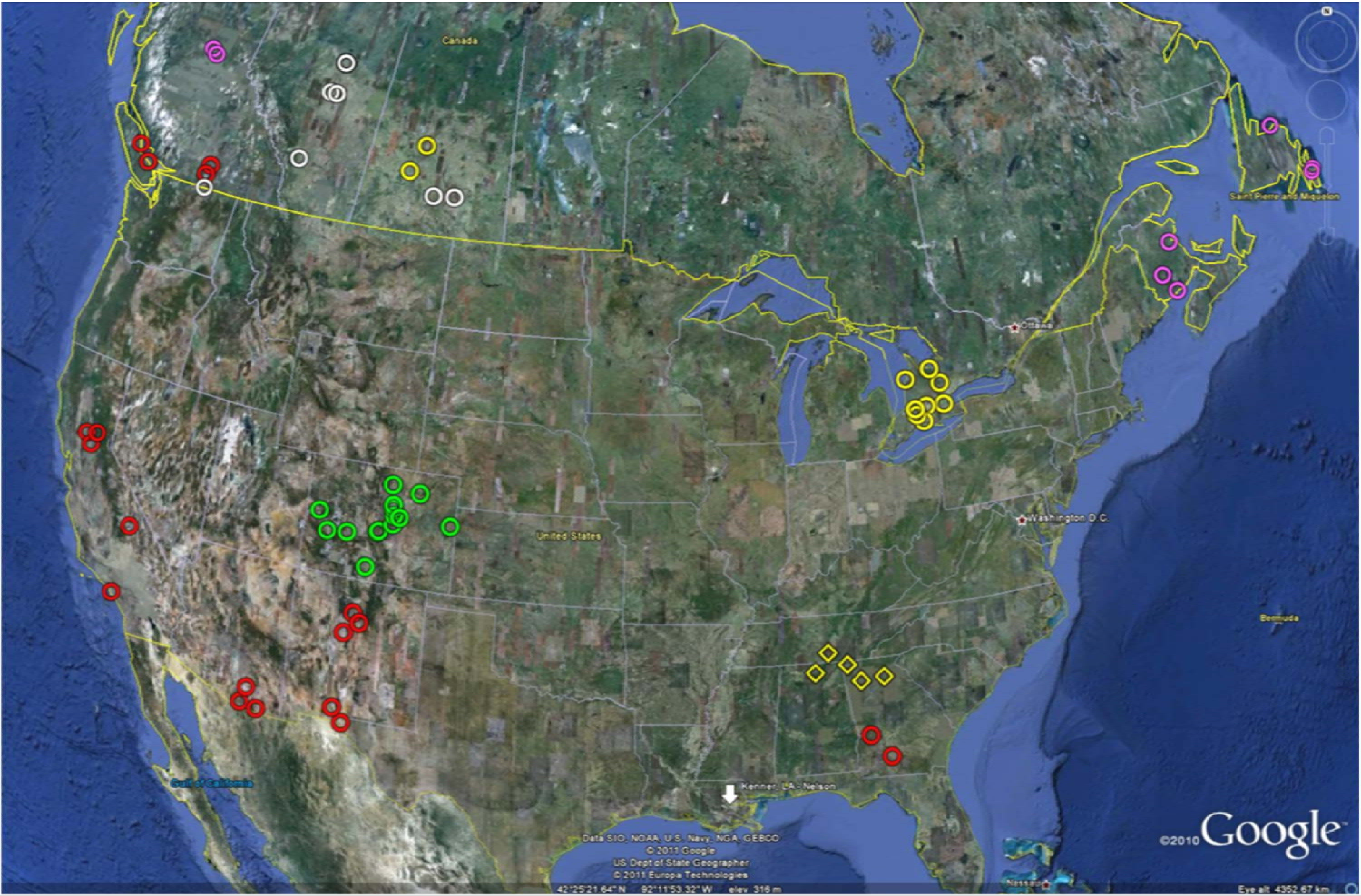
- Can see fainter meteors than Super Schmidt cameras
- Video frame rates (30 frames per second) give better time resolution than a rotating shutter
- Unrivaled time accuracy using GPS time stamps




Cons

- Limited resolution compared to photographic detection
- Cameras saturate easily

# Video Meteor Networks in North America



# Radar Meteor Detection

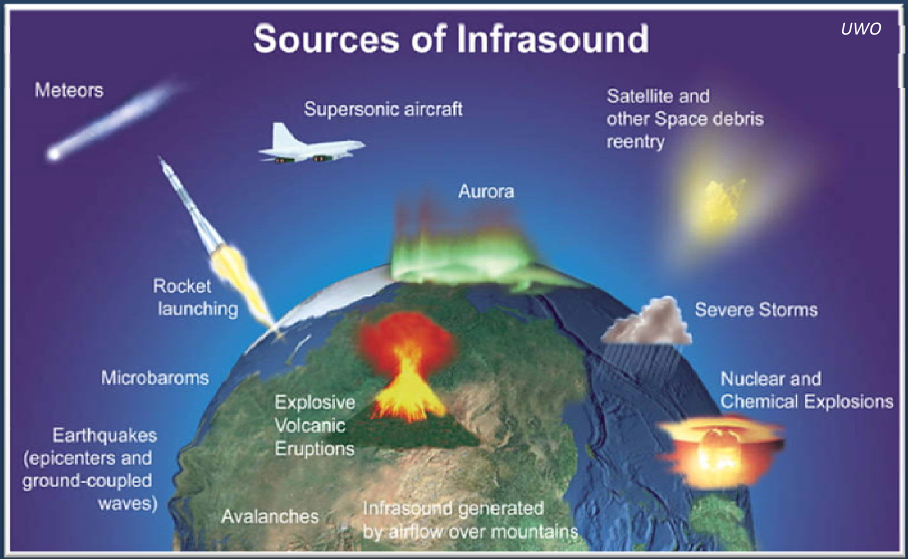
- Radio waves can reflect off meteor trails
- Canadian Meteor Orbit Radar sees 10,000+ meteors per day


Pros
- 24 hour per day detection
- Large portion of sky observed (patrol type radars)
- Can see very small particles
- Automated

Cons
- Expensive
- Small portion of the sky observed (HPLA type radars)
- Difficulty detecting shower meteors

# Infrasound Meteor Detection

- Infrasound is sound made by natural and man-made sources, below the wavelength of human hearing.
- Emitted by avalanches, earthquakes, some animals (elephants, whales), and meteors!
- Infrasonic waves are capable of propagating over great distances.
- The shock waves produced by a large meteor can be detected.



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# NASA Fireball Project

- A network of video cameras pointed at the sky (all-sky cameras) set up to detect fireballs (bright meteors)
- Meteors are automatically detected using special software
- Video of each meteor is recorded
- Computers on the network communicate over the internet to find meteors seen by more than 1 all-sky camera
- Data analysis is done automatically and the results are posted on a public website

# System Components

- All-sky Camera
  - Roof mount
  - Video cable
  - Power cable


- Computer running ASGARD software
  - **A**ll **S**ky and **G**uided **A**utomatic **R**eal-time **D**etection
  - Uninterruptible Power Supply (UPS)
  - Internet connection

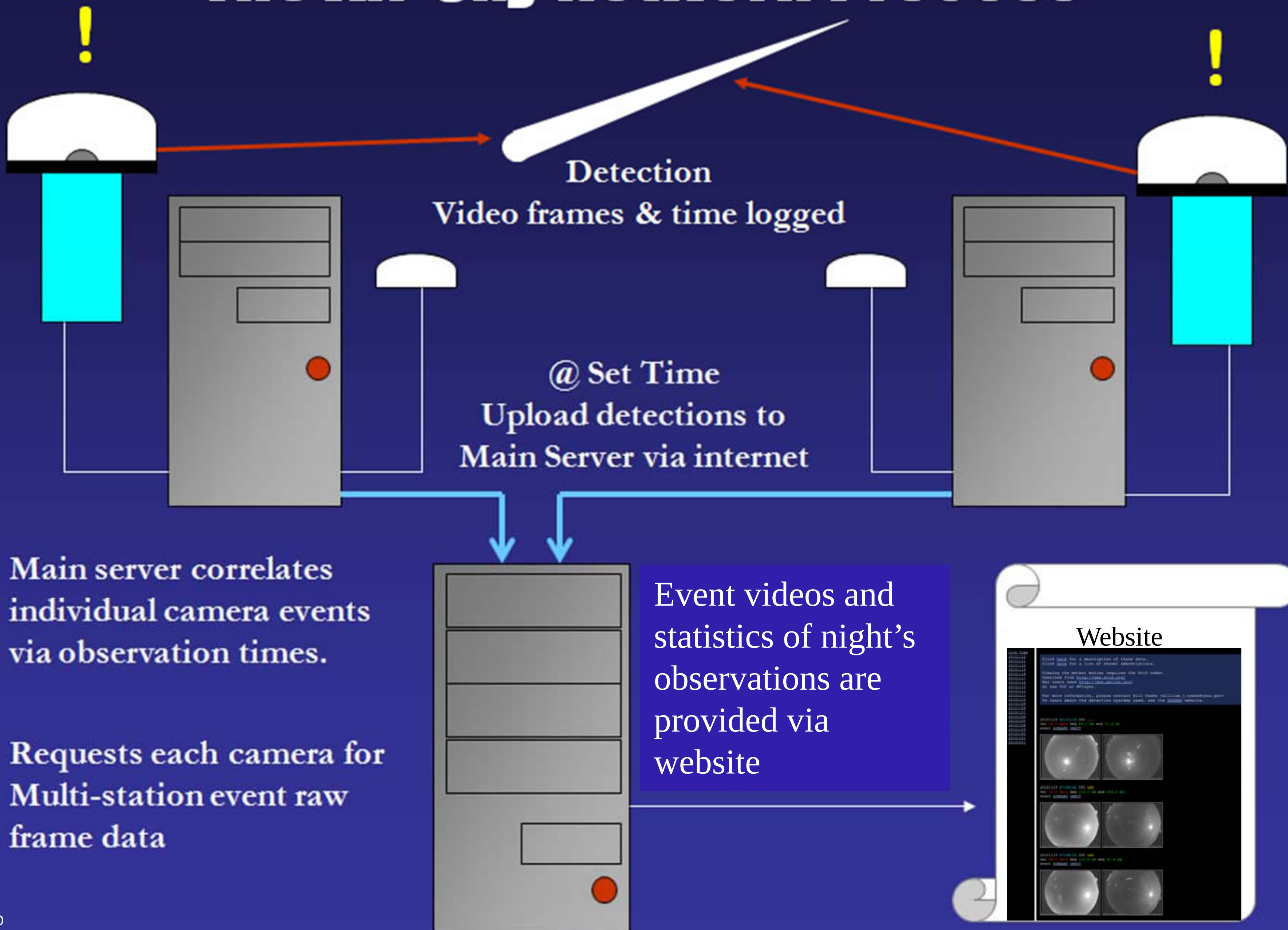
- GPS

# All-Sky Cameras

Low-light black and white video cameras with all-sky lenses.

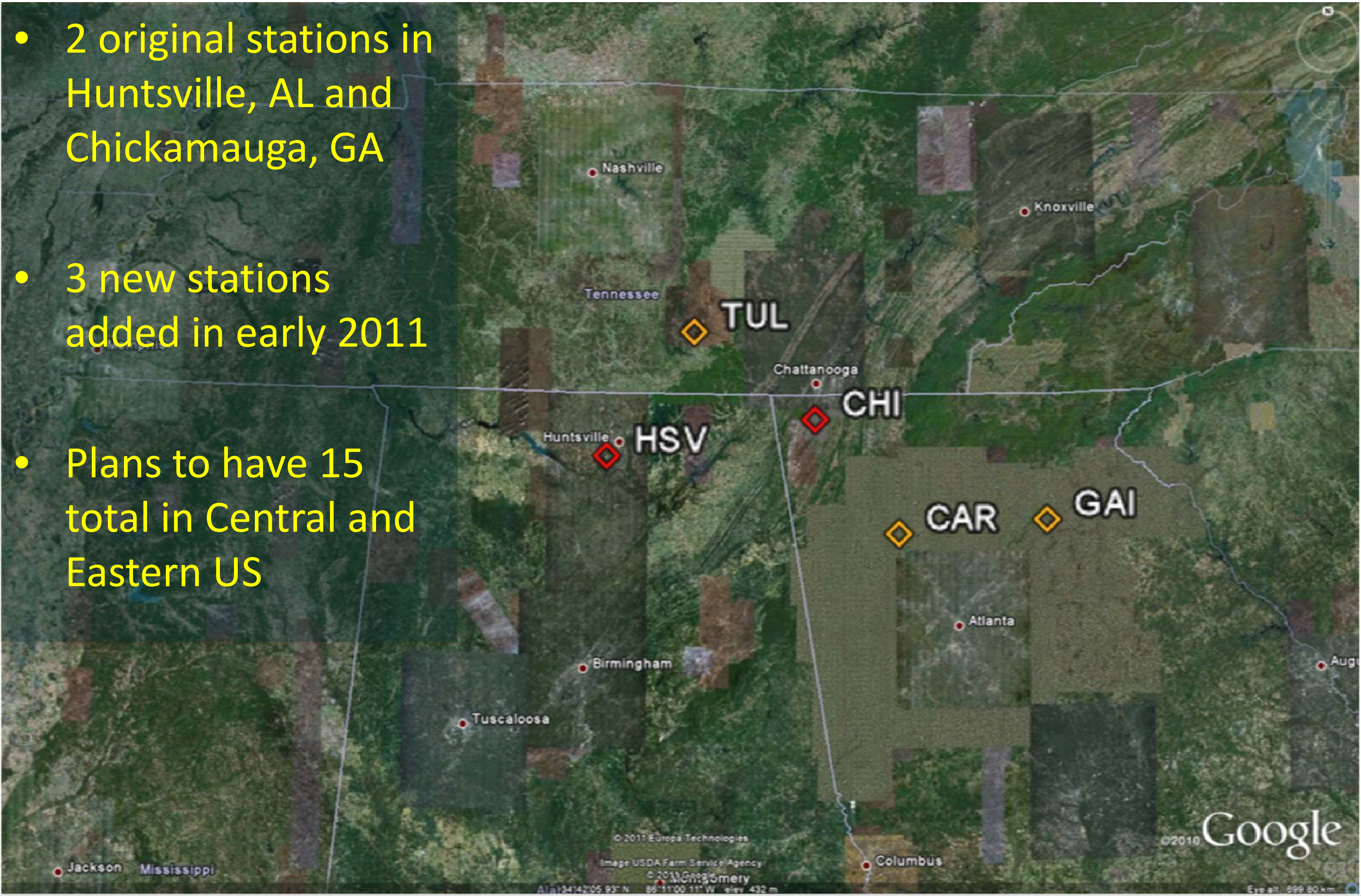
The enclosure has a thermostat for heating during winter and a fan system to circulate air and prevent dewing of lenses or the dome.

# The All-Sky Network Process



# Camera Network

- 2 original stations in Huntsville, AL and Chickamauga, GA
- 3 new stations added in early 2011
- Plans to have 15 total in Central and Eastern US

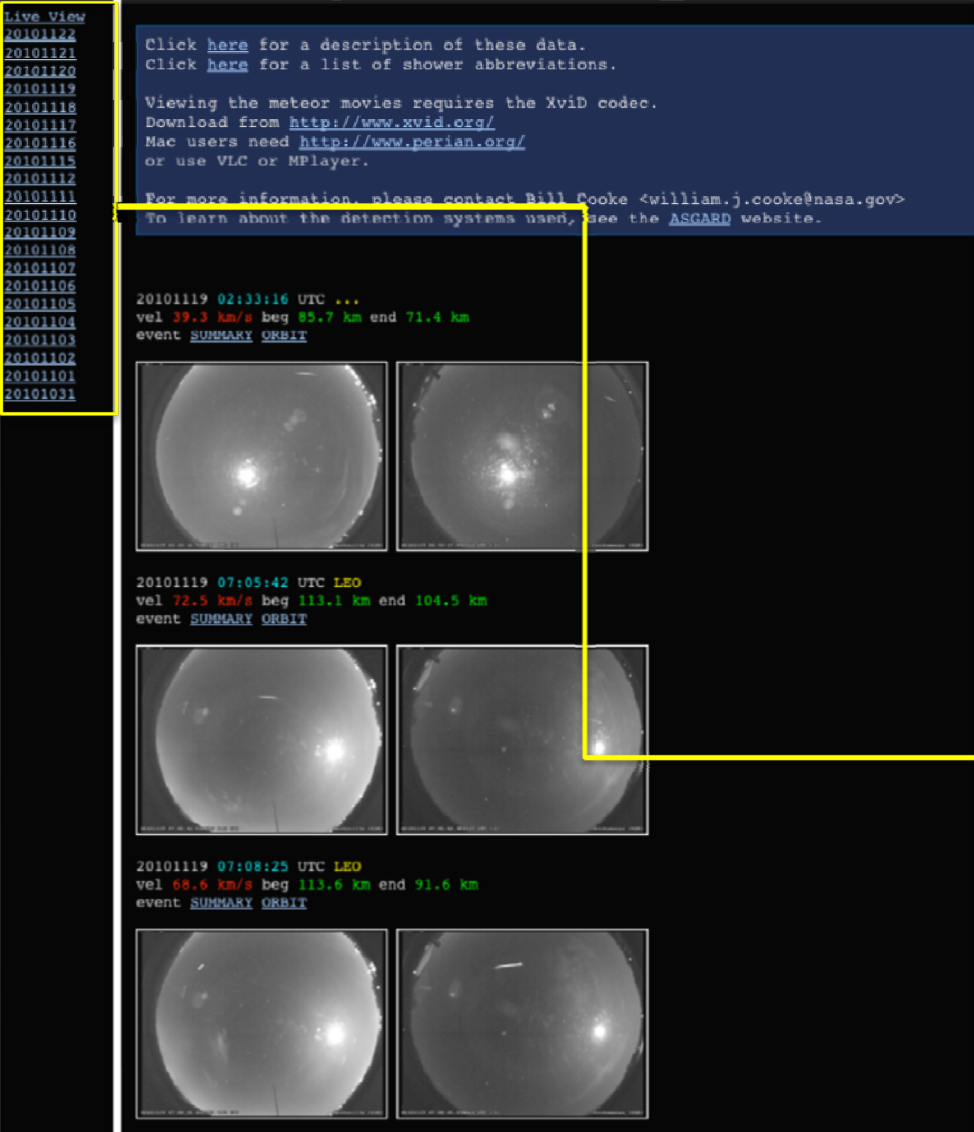


# Results Website

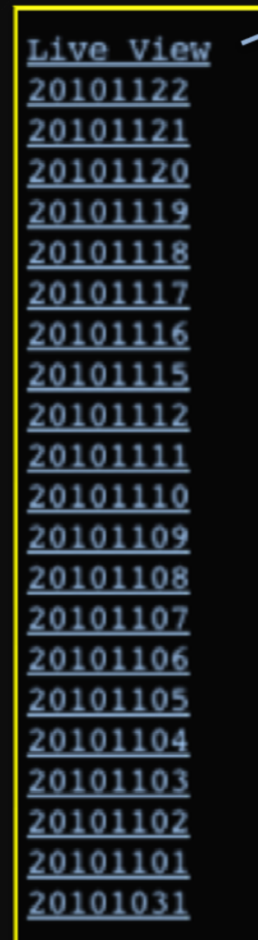

*http://fireballs.ndc.nasa.gov/*

Daily weblog of events seen on the camera network.

Information derived from the two original stations is seen here. As more cameras are added to the network, you'll see more images.




# Results Website



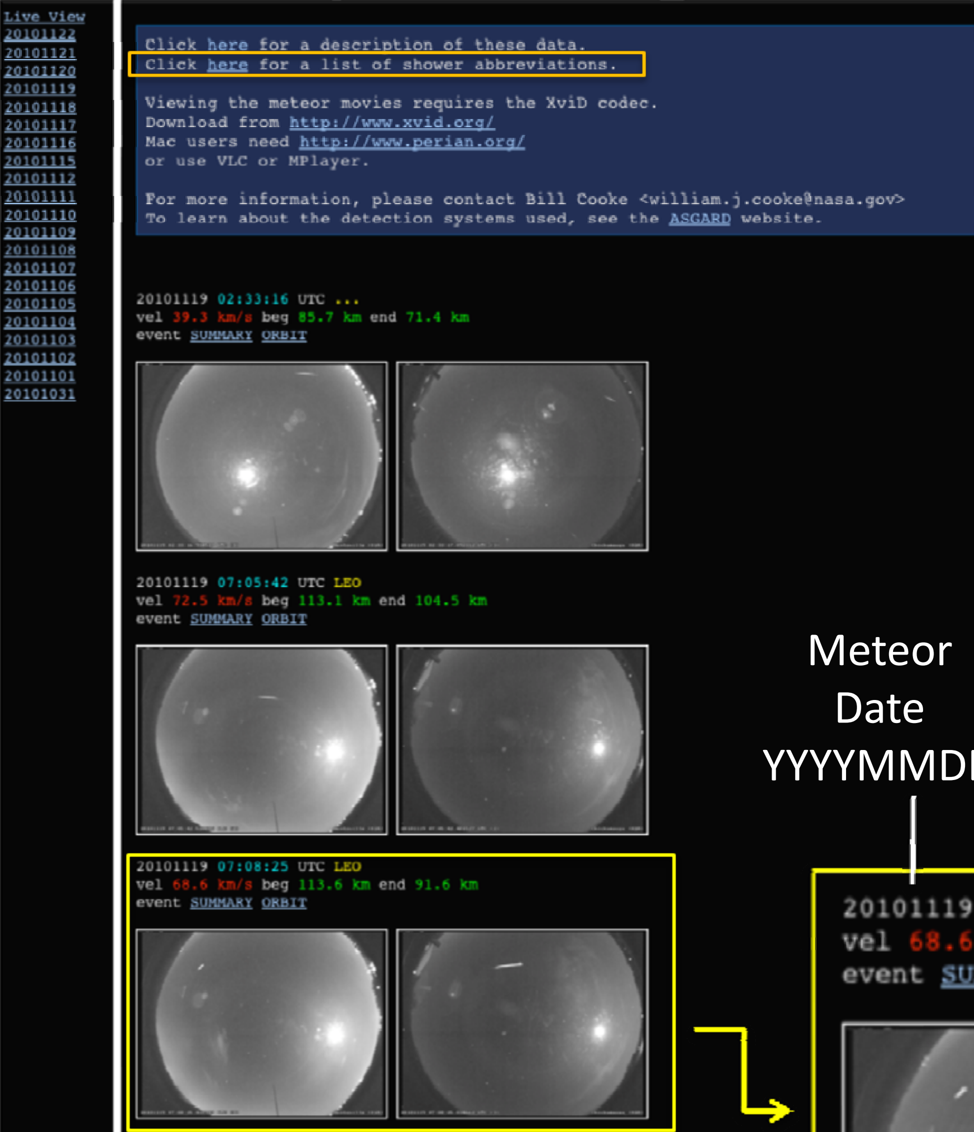

Shows the current camera view (it's off during the day)

Each date is a link to meteor events seen on that day

Some links may show a blank page. This is because no meteor events were detected that day (usually because of weather)

Only last 3 weeks of data available online

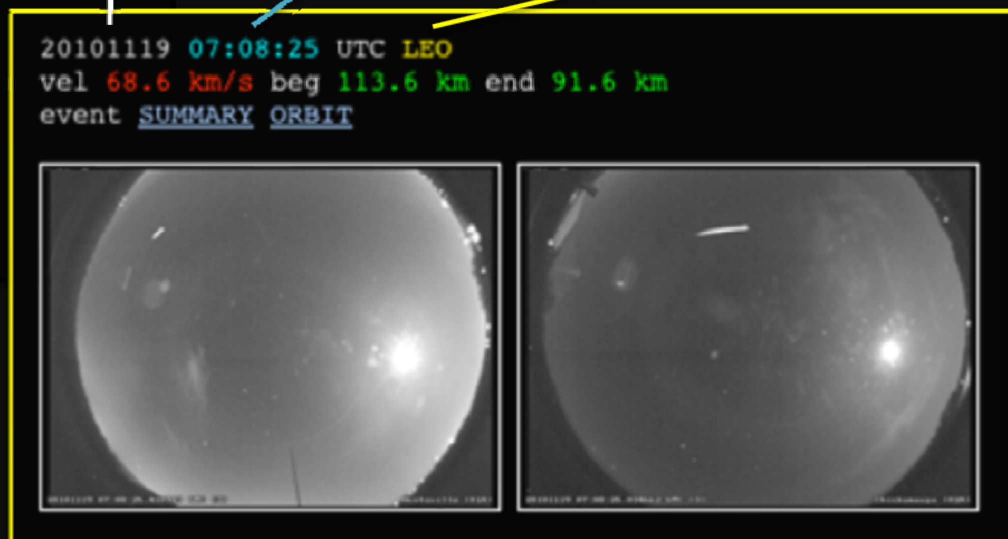
# Results Website




Meteor Date YYYYMMDD

Meteor Time (UTC) hh:mm:ss

3 letter shower abbreviation (will be shown as ... if sporadic)



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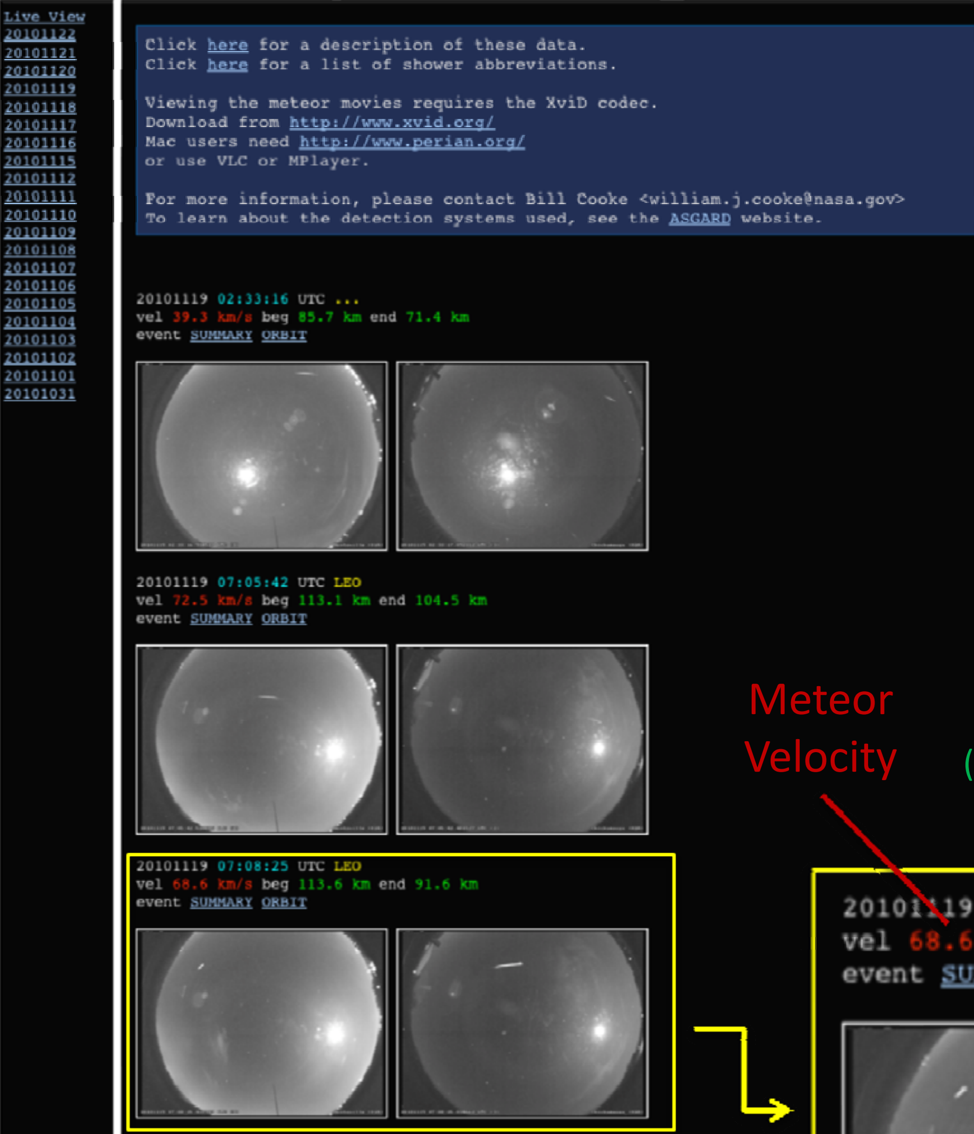
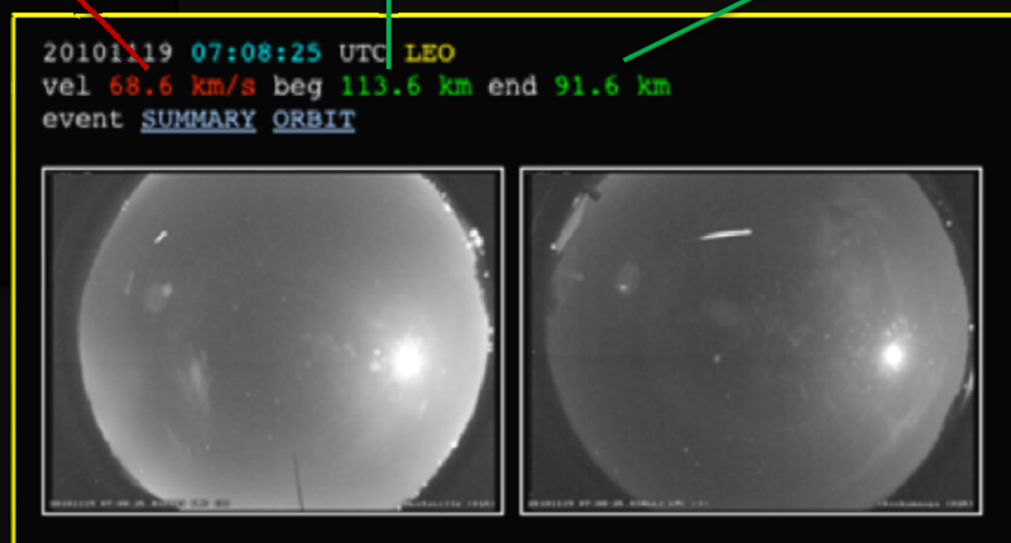


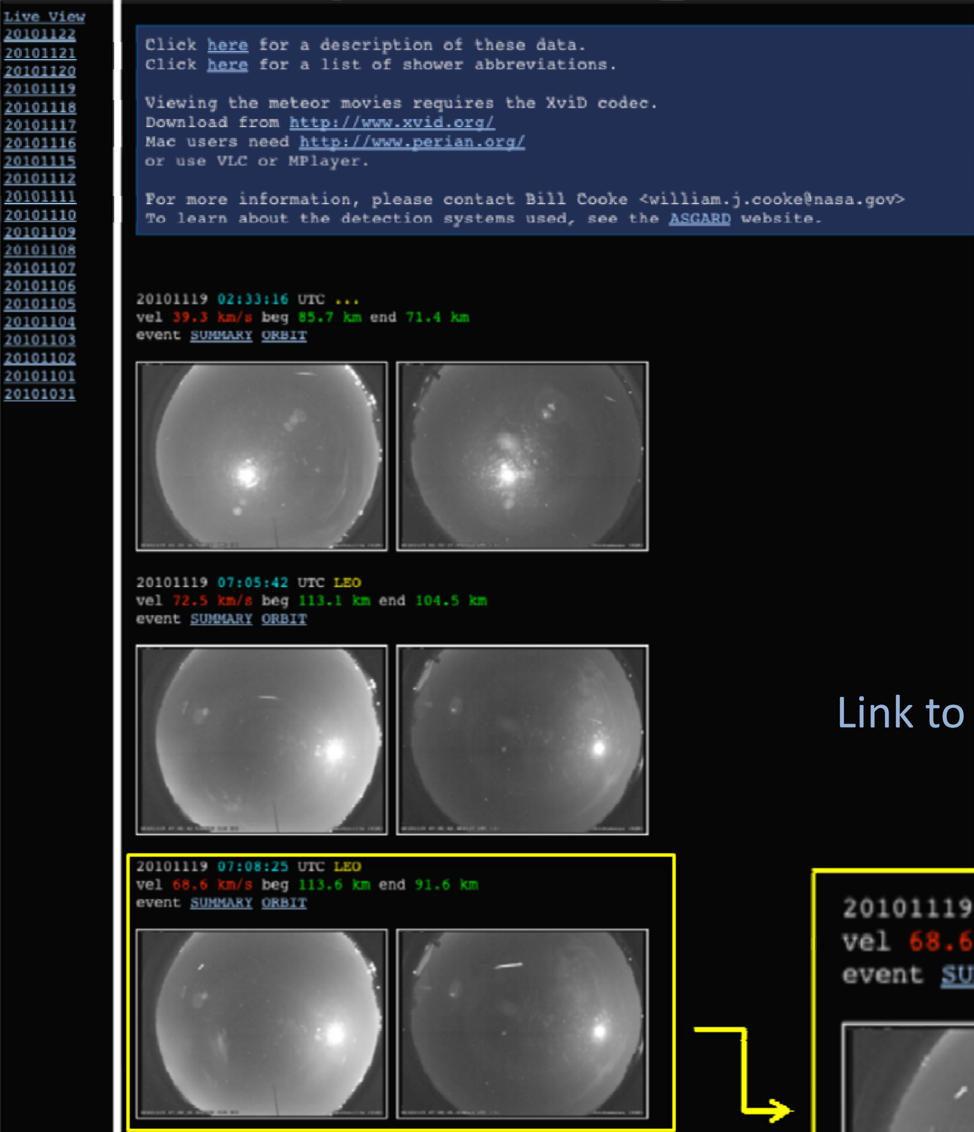

Meteor Velocity

Beginning Height (height meteor first detected)

Ending Height (height meteor last detected)

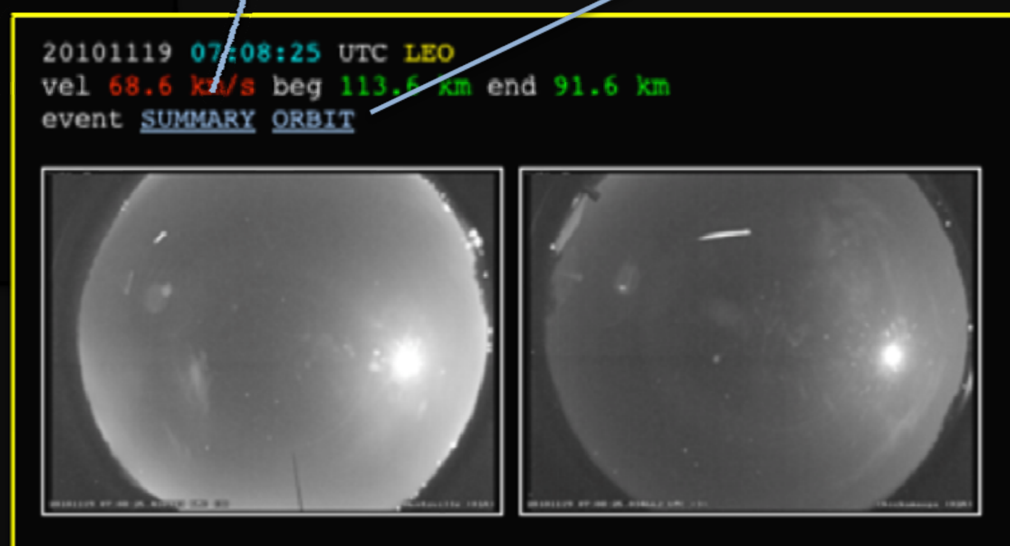


# Results Website




Link to Summary Graphic

Link to Orbit Data



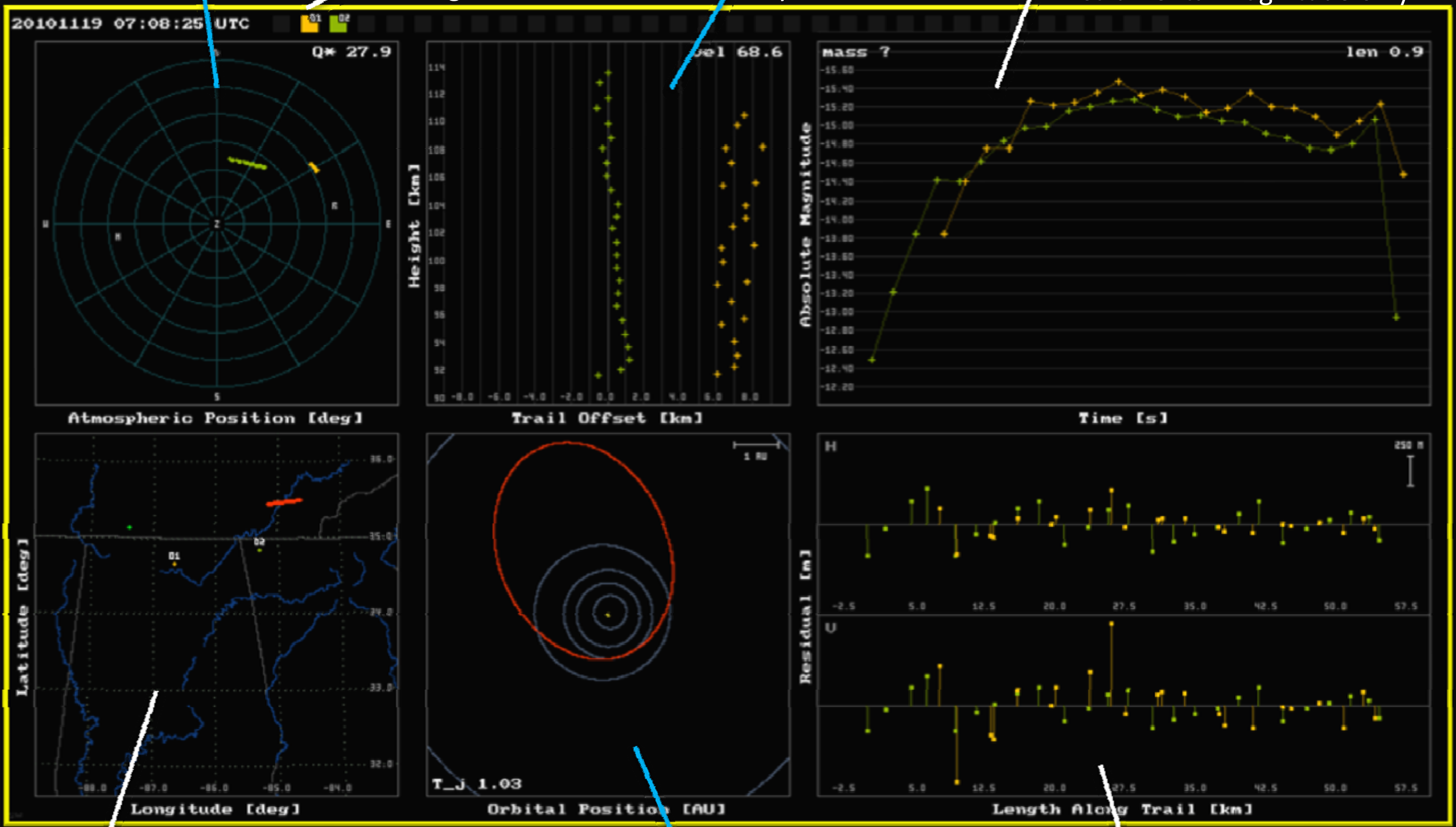
# Results Website: Summary Graphic

Apparent path of meteor in sky

Vertical/slight diagonal lines: meteor moving at constant speed
Curved lines: meteor is decelerating as it moves

Meteor lightcurve = brightness over time
Instrumental magnitude only

Color legend: results color-coded by station




Meteor path over U.S. (red)
Trajectory extrapolated to ground (green dot)

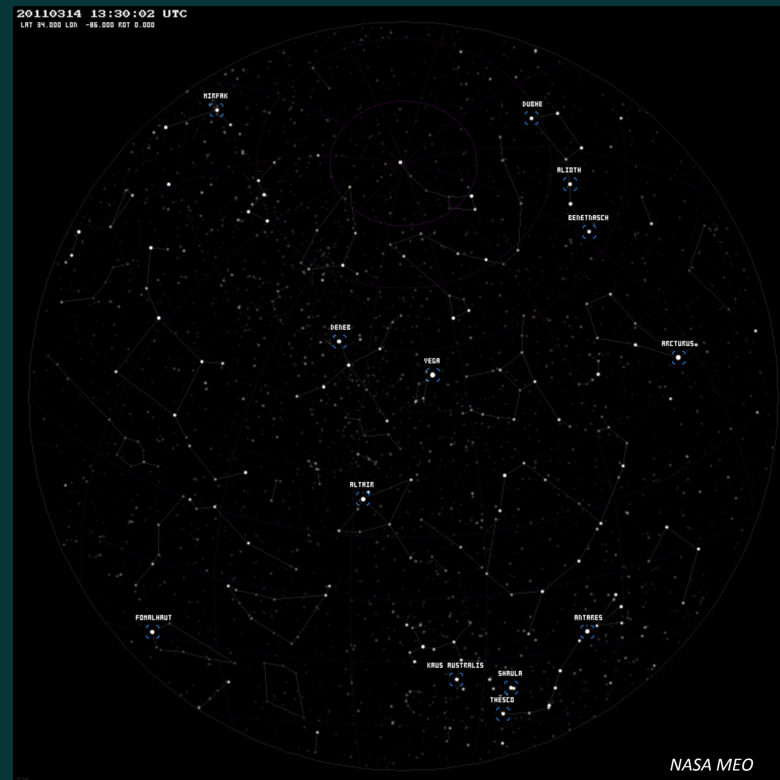
Meteor orbit in space (red)
Planetary orbits (gray)

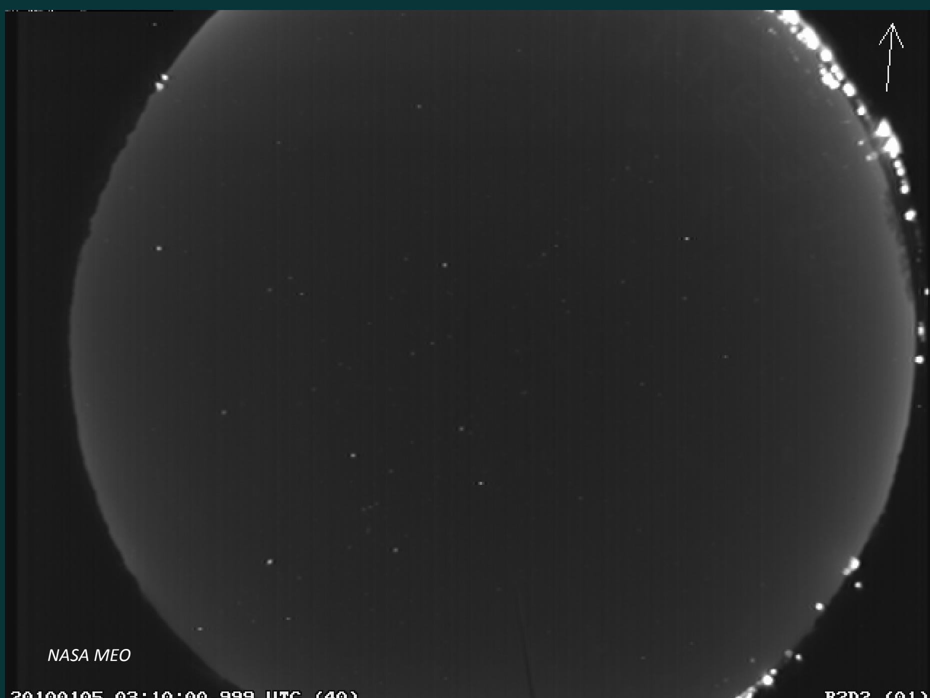
Errors of the trajectory determination in the horizontal (H) and vertical (V) directions

# Calibrate with Known Stars

To find position

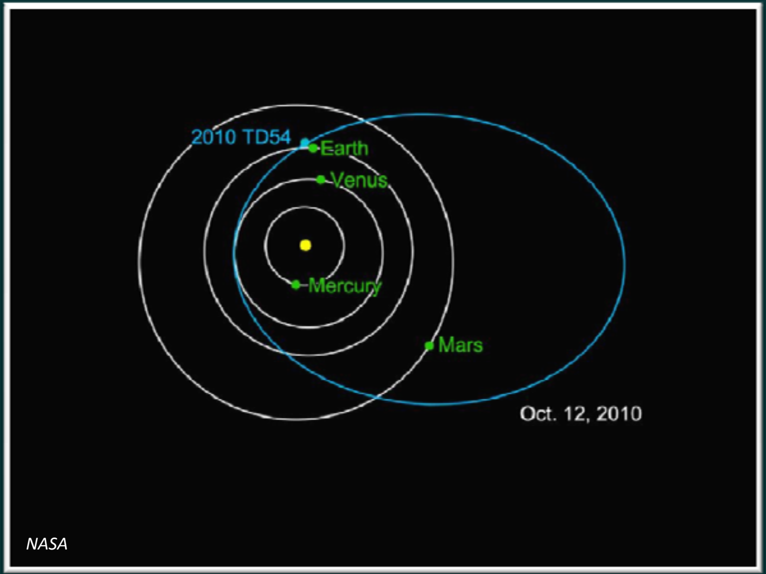
And brightness



# Orbit of a Meteor

- Its path in space
- Can tell us which group of comets the meteor was originally from
    - Jupiter Family Comets
    - Halley-Type Comets




- We need at least two cameras to calculate an orbit…
    – One camera can tell us the velocity and height

# Results Website: Orbit Data

```
time 20101119 7.1403 hours
 lat  35 26 00.096 =  35.4334 deg
 lon 274 50 01.536 = 274.8338 deg
  ht 0.000 b 13.83505 -0.64761 10.28211 17.42780
      alp 155.179 +/-  0.174 deg
      del  20.491 +/-  0.562 deg
    v_inf  68.565 +/-  1.831 km/s
    v_avg  68.565 +/-  1.831 km/s

        a   2.503 +/-  0.987 AU
        e   0.609 +/-  0.153
     incl 162.970 +/-  1.000 deg
    omega 167.164 +/-  2.717 deg
 asc_node 236.694 +/-  0.000 deg
      v_g  67.298 +/-  1.857 km/s
      v_h  37.958 +/-  1.841 km/s
  alp_geo 155.408 +/-  0.178 deg
  del_geo  20.396 +/-  0.568 deg
    q_per   0.979 +/-  0.003 AU
    q_aph   4.027 +/-  1.972 AU
   lambda 149.924 +/-  0.264 deg
     beta   9.474 +/-  0.532 deg
true anom  12.840 +/-  0.532 deg

      T_j    1.0
       jd 2455519.79751
     slon 236.69062 deg
      sid 80.14739 deg
       Q*  27.927 deg
```

Time – date and time of the event; written as YYYYMMDD and fractional hours

Geographic coordinates (lat, lon) – latitude and longitude of the meteor’s end point in Earth-based geographic coordinates

Radiant position (alp, del) – location of the radiant in equatorial coordinates, right ascension and declination

Meteor velocity (v_inf, v_avg) – speed of the meteor

Semi-major axis (a) – size of the ellipse; half the major axis of the ellipse

Eccentricity (e) – shape of the ellipse; measures how far from a circular shape the orbit is

# Results Website: Orbit Data

```
time 20101119 7.1403 hours
 lat  35 26 00.096 =  35.4334 deg
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      T_j   1.0
       jd 2455519.79751
     slon 236.69062 deg
      sid 80.14739 deg
       Q*  27.927 deg
```

Inclination (incl, i) – vertical tilt of the ellipse with respect to the ecliptic plane; angle between the body's orbital plane and the ecliptic

Argument of perihelion (omega, ω) – defines the orientation of the ellipse; angle between the ascending node and semi-major axis

Longitude of ascending node (asc_node, Ω) – horizontally orients the ascending node of the ellipse; angle between the vernal equinox and the ascending node

Geocentric velocity (v_g) – velocity of the meteoroid with respect to Earth

Heliocentric velocity (v_h) – velocity of the meteoroid with respect to the Sun

Geocentric radiant position (alp_geo, del_geo) – location of the radiant in geocentric equatorial coordinates

# Results Website: Orbit Data

```
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      T_j    1.0
       jd 2455519.79751
     slon 236.69062 deg
      sid 80.14739 deg
       Q*  27.927 deg
```

Perihelion distance (q_per) – minimum distance from the Sun that the meteoroid reaches along its elliptical orbit

Aphelion distance (q_aph) – maximum distance from the Sun that the meteoroid reaches along its elliptical orbit

Ecliptic latitude and longitude (beta, lambda) – coordinates describing the position of the meteoroid in the ecliptic coordinate system

True anomaly (true anom) – the angle that the meteoroid has moved since last passing perihelion

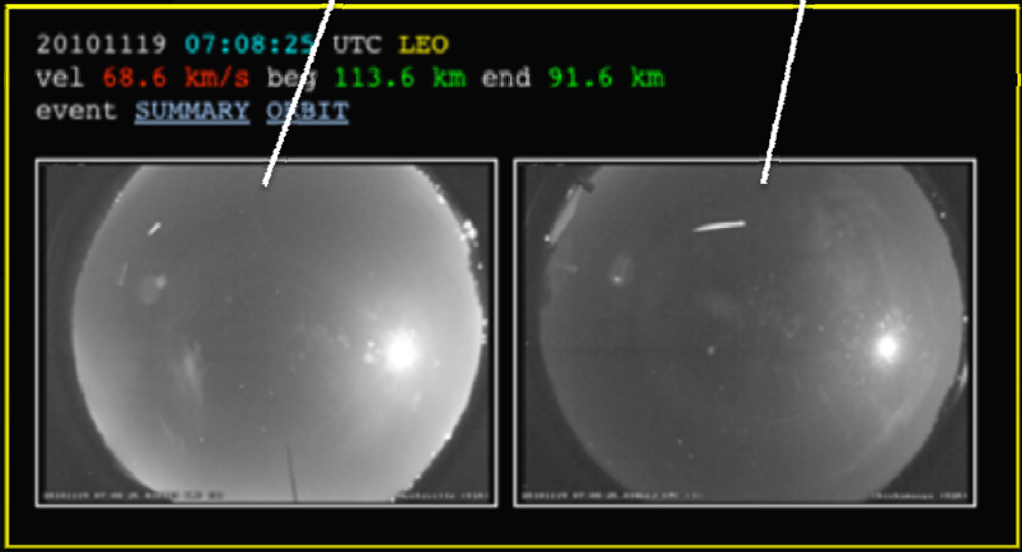
Tisserand parameter with respect to Jupiter (T_j) – is a relation of orbital elements a, e, and i typically used to distinguish asteroids from Jupiter family comets

Julian date (jd) – astronomical measure of time; the interval of time in days since Jan 1, 4713 BC in the Julian calendar.

# Results Website


Video of meteor from station 1

Video of meteor from station 2



# Results Website:
## Video of Meteor Detected by 2 Cameras


Video from Huntsville


Video from Chickamauga

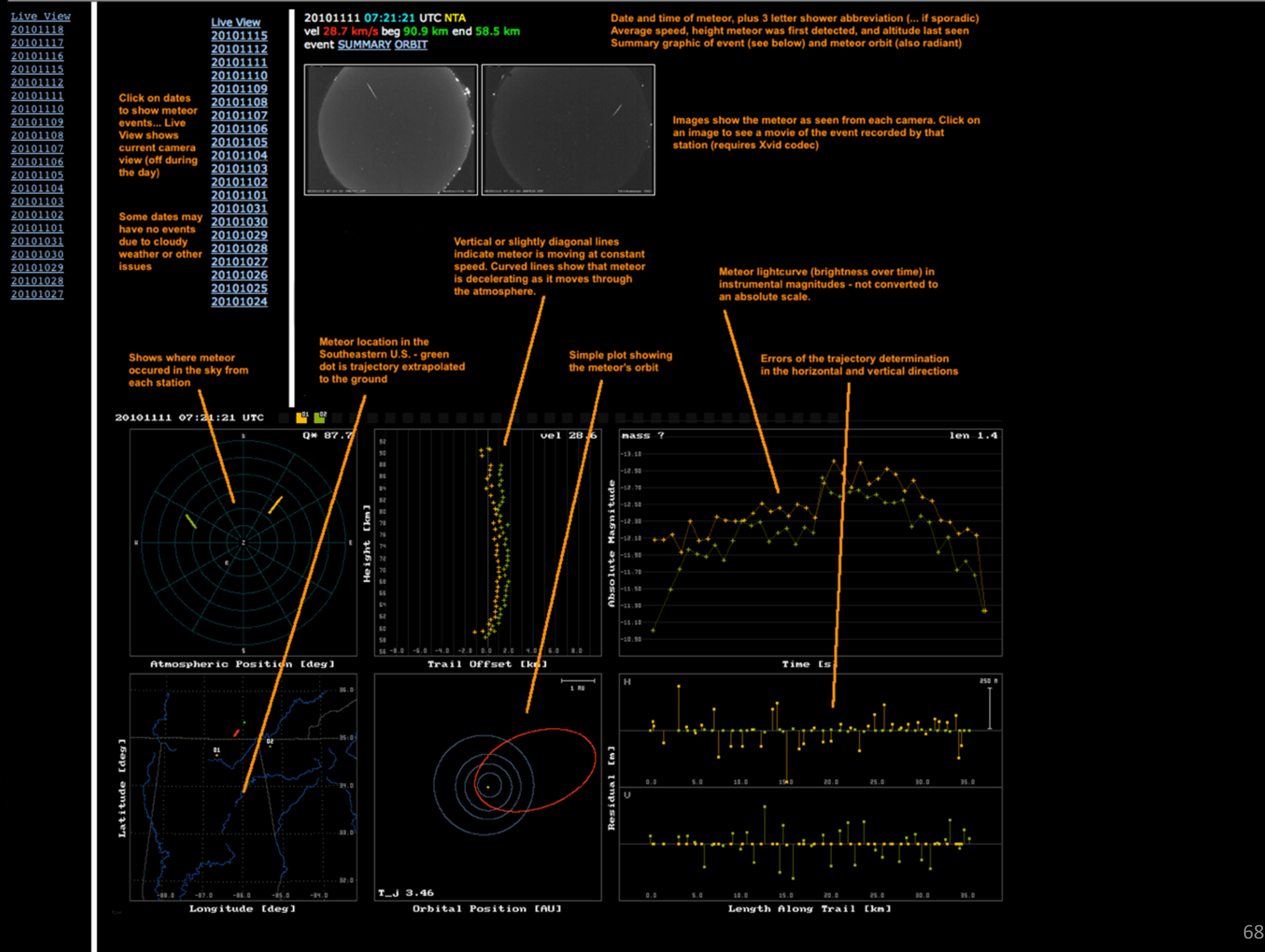
North

East

# Results Website

## And in case you forget what all this means…


A description of the data can be found on the website


Live View
20101118
20101117
20101116
20101115
20101112
20101111
20101110
20101109
20101108
20101107
20101106
20101105
20101104
20101103
20101102
20101101
20101031
20101030
20101029
20101028
20101027
Click on dates to show meteor events... Live View shows current camera view (off during the day)
Some dates may have no events due to cloudy weather or other issues
Live View
20101115
20101112
20101111
20101110
20101109
20101108
20101107
20101106
20101105
20101104
20101103
20101102
20101101
20101031
20101030
20101029
20101028
20101027
20101026
20101025
20101024
20101111 07:21:21 UTC NTA
vel 28.7 km/s beg 90.9 km end 58.5 km
event SUMMARY ORBIT
Date and time of meteor, plus 3 letter shower abbreviation (... if sporadic)
Average speed, height meteor was first detected, and altitude last seen
Summary graphic of event (see below) and meteor orbit (also radiant)
Images show the meteor as seen from each camera. Click on an image to see a movie of the event recorded by that station (requires Xvid codec)
Vertical or slightly diagonal lines indicate meteor is moving at constant speed. Curved lines show that meteor is decelerating as it moves through the atmosphere.
Meteor lightcurve (brightness over time) in instrumental magnitudes - not converted to an absolute scale.
Shows where meteor occured in the sky from each station
Meteor location in the Southeastern U.S. - green dot is trajectory extrapolated to the ground
Simple plot showing the meteor's orbit
Errors of the trajectory determination in the horizontal and vertical directions
20101111 07:21:21 UTC
Q* 87.7
vel 28.6
mass ?
len 1.4
Height [km]
Absolute Magnitude
Atmospheric Position [deg]
Trail Offset [km]
Time [s]
Latitude [deg]
Residual [m]
T_J 3.46
Longitude [deg]
Orbital Position [AU]
Length Along Trail [km]

# Results Website

## Additional Information

# False Alarms

Occasionally the ASGARD software will flag a plane, satellite, bug, lightning, headlights, etc, as a meteor.

Iridium Flare

Airplane


Bird

Bug


Lightning

Headlight Glare

*Videos from UWO*

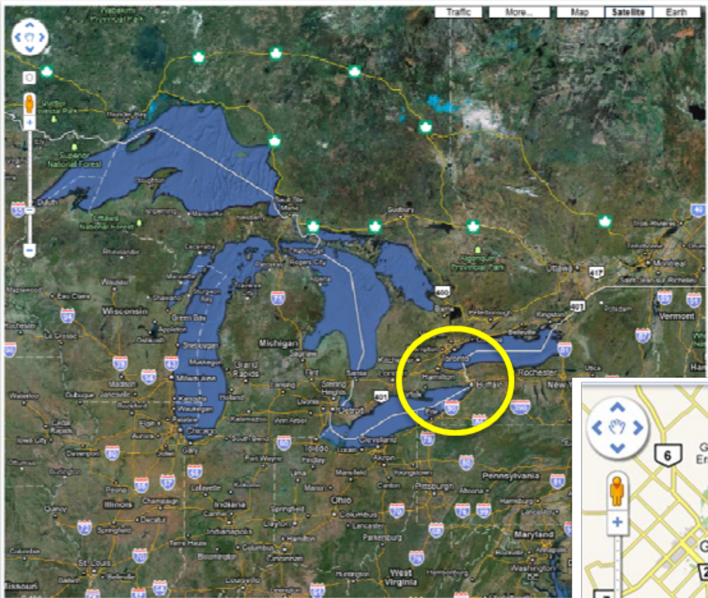
# Purpose of the NASA Fireball Project

- Meteors in this cm-size-range correlate to mass loss from comets
- Compare the ablation of meteors with models
- Compare meteors detected with these video cameras to the same meteor detected with radar, infrasound, etc
- If a detection was thought to produce meteorites, we would be able to see its orbit, velocity, have a recording of how it ablated, and then study its actual composition

# Example: Grimsby Meteor Video

UWO

# Grimsby Fireball Path

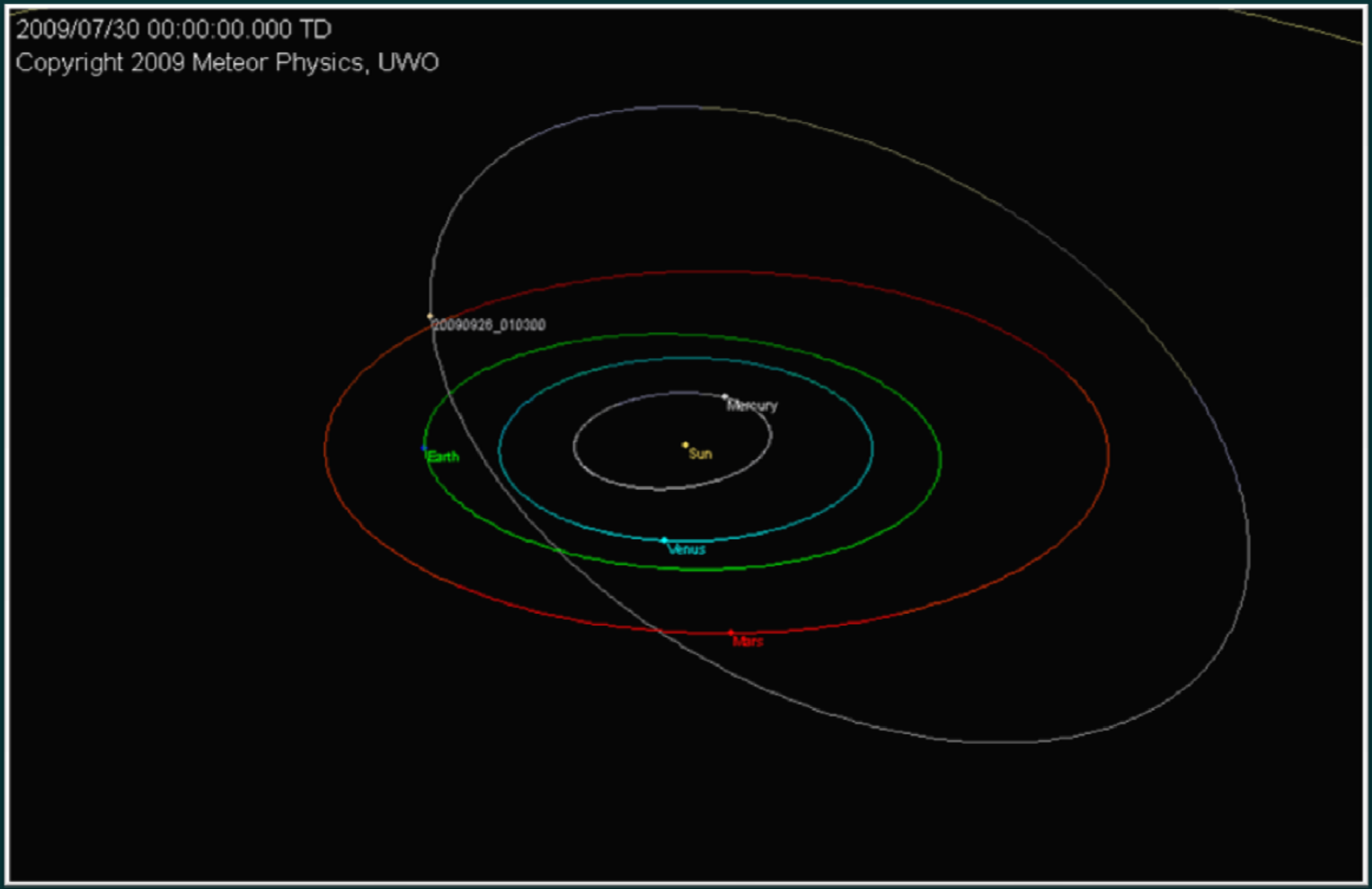







Chemical composition analysis was able to be performed along with many other aspects.

# Simulation of rock from outer space to Earth…



# Outline

A. Background
   I. Terminology – meteors, comets, asteroids, etc
   II. Motivation – why do we study this?
   III. Methods – how do we study meteors?
B. All-Sky Cameras
   I. System Components
   II. Website
   III. Case Study: Grimsby
C. Use in the Classroom

Break!

# Outline

A. Background
   I. Terminology – meteors, comets, asteroids, etc
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   I. System Components
   II. Website
   III. Case Study: Grimsby
C. Use in the Classroom

# Goals

- Data Collection and Record Keeping
  - Use appropriate technology to store and retrieve scientific information in topical, alphabetical, numerical, and keyword files, and create simple files.
- Retrieving Information
  - Organize scientific information using appropriate tables, charts, and graphs
- Analysis
  - Identify the relationships revealed via tables, chart, and graphs
  - Formulate explanations to make sense of collected data

Students can create a database of meteors, mine data to explore various topics.

# Format of this Section

- Data example
  - Sample questions
- Related lessons
- Related tools

# Data Analysis

- How many Perseids were seen in 2010? 76

- How fast do Perseids travel?

  59.346 km/s on average

  59.3 km/s on average, using sig figs

- How does this compare to the value reported by the IMO?

  The IMO gives 59 km/s as the speed of the Perseids. This agrees with the fireball data using 2 sig figs. We can also calculate

  % error = 0.51%

  % difference = 0.51%

Given a table of data about Perseids

| date | time | speed km/s |
|---|---|---|
| 20100802 | 5:45:50 | 55.7 |
| 20100803 | 8:59:41 | 60.6 |
| 20100804 | 2:56:00 | 59.8 |
| 20100804 | 7:18:33 | 58.4 |
| 20100805 | 7:52:41 | 59.2 |
| 20100805 | 8:25:57 | 54.3 |
| 20100805 | 9:14:57 | 58.7 |
| 20100805 | 9:42:26 | 58.4 |
| 20100805 | 10:01:49 | 58.3 |
| 20100807 | 8:35:10 | 63.0 |
| 20100808 | 4:36:01 | 59.5 |
| 20100808 | 7:16:56 | 56.1 |
| 20100808 | 8:38:38 | 60.0 |
| 20100808 | 9:23:54 | 59.4 |
| 20100809 | 3:47:02 | 63.3 |
| 20100809 | 6:14:45 | 56.4 |
| 20100809 | 7:40:46 | 57.0 |
| 20100809 | 9:27:31 | 61.1 |
| 20100810 | 7:34:30 | 60.2 |
| 20100810 | 8:20:26 | 59.1 |
| 20100810 | 8:55:06 | 58.4 |
| 20100810 | 9:10:53 | 58.4 |
| 20100810 | 9:10:59 | 60.7 |
| 20100810 | 10:03:37 | 59.0 |
| 20100811 | 4:07:38 | 60.0 |
| 20100811 | 8:09:58 | 60.4 |
| 20100811 | 8:16:51 | 59.9 |
| 20100811 | 9:19:05 | 61.7 |
| 20100812 | 5:50:57 | 58.8 |
| 20100812 | 6:33:25 | 62.1 |
| 20100812 | 7:19:51 | 59.2 |
| 20100812 | 7:54:29 | 56.7 |
| 20100812 | 8:08:40 | 59.7 |
| 20100812 | 8:35:24 | 60.4 |
| 20100812 | 8:38:15 | 61.5 |
| 20100812 | 8:53:30 | 56.9 |
| 20100812 | 8:55:30 | 59.5 |
| 20100812 | 9:17:58 | 56.4 |
| 20100812 | 9:28:41 | 59.0 |
| 20100812 | 9:30:48 | 57.0 |
| 20100812 | 9:36:40 | 54.2 |
| 20100813 | 3:01:29 | 59.2 |
| 20100813 | 4:55:01 | 69.0 |
| 20100813 | 5:07:40 | 59.9 |
| 20100813 | 5:44:44 | 60.9 |

NASA MEO

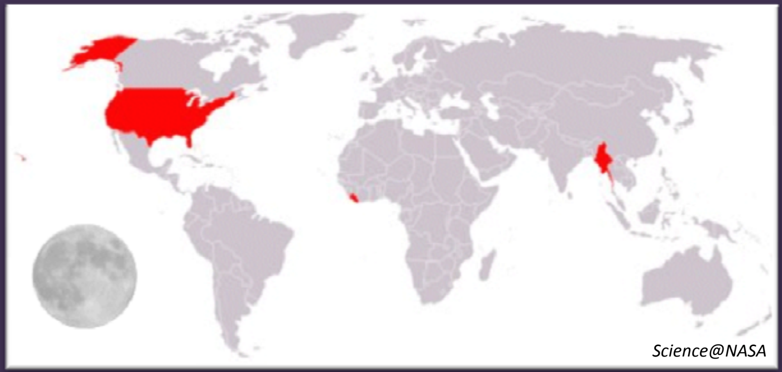
| date | time | speed km/s |
|---|---|---|
| 20100813 | 6:23:22 | 66.3 |
| 20100813 | 6:24:31 | 60.0 |
| 20100813 | 6:34:56 | 58.9 |
| 20100813 | 7:12:05 | 58.0 |
| 20100813 | 7:26:44 | 59.6 |
| 20100813 | 7:32:48 | 58.3 |
| 20100813 | 7:40:21 | 64.6 |
| 20100813 | 7:41:29 | 61.6 |
| 20100813 | 7:44:52 | 59.3 |
| 20100813 | 7:53:04 | 57.8 |
| 20100813 | 8:33:08 | 61.4 |
| 20100813 | 8:47:08 | 58.5 |
| 20100813 | 8:47:18 | 52.6 |
| 20100813 | 8:51:42 | 61.2 |
| 20100813 | 9:07:30 | 59.9 |
| 20100813 | 9:23:50 | 57.9 |
| 20100813 | 9:29:01 | 59.2 |
| 20100813 | 9:56:54 | 59.4 |
| 20100813 | 9:58:40 | 57.1 |
| 20100813 | 10:06:38 | 58.8 |
| 20100814 | 5:03:21 | 59.2 |
| 20100814 | 5:12:02 | 59.4 |
| 20100814 | 6:24:42 | 57.8 |
| 20100814 | 6:25:46 | 59.0 |
| 20100814 | 7:10:12 | 59.2 |
| 20100814 | 8:13:26 | 59.3 |
| 20100814 | 8:17:53 | 60.5 |
| 20100814 | 8:55:33 | 58.6 |
| 20100814 | 9:09:48 | 59.2 |
| 20100815 | 7:08:47 | 63.6 |
| 20100815 | 10:06:12 | 56.7 |

NASA MEO

Students can collect and record data themselves or work from a given table

# Related Lesson:  Metric Units

- The units of speed and height on the results website are metric units
- Unit abbreviations (km, m)



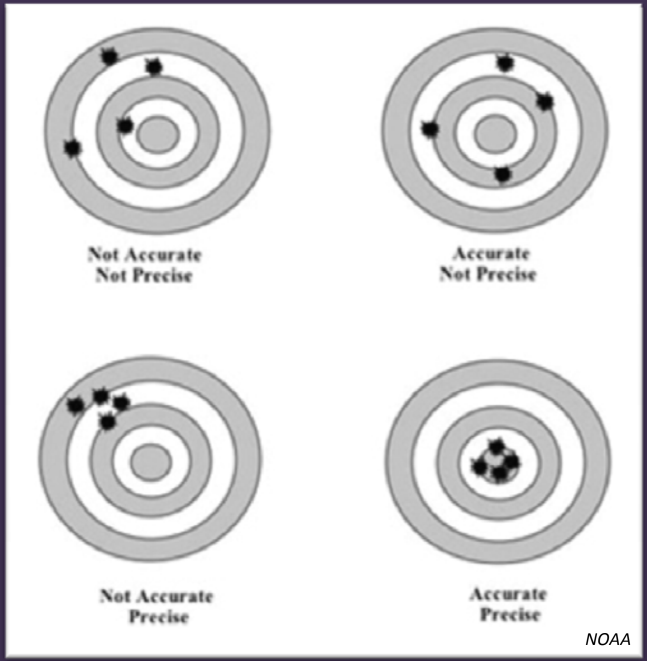

- Unit conversion
  - Convert speed, kilometers per second (km/s) to meters per second (m/s)
  - Convert height, kilometers (km), to meters (m)

# Related Lesson:  Significant Figures

- What are significant figures and why are they important
- Rules for deciding the number of significant figures in a measured quantity
- Math with significant figures

# Related Lesson: Accuracy vs. Precision

- What's the difference between accuracy and precision and the importance of each?
  - Accuracy: how close the measured quantity is to its real value
  - Precision: degree to which repeated measurements show the same results



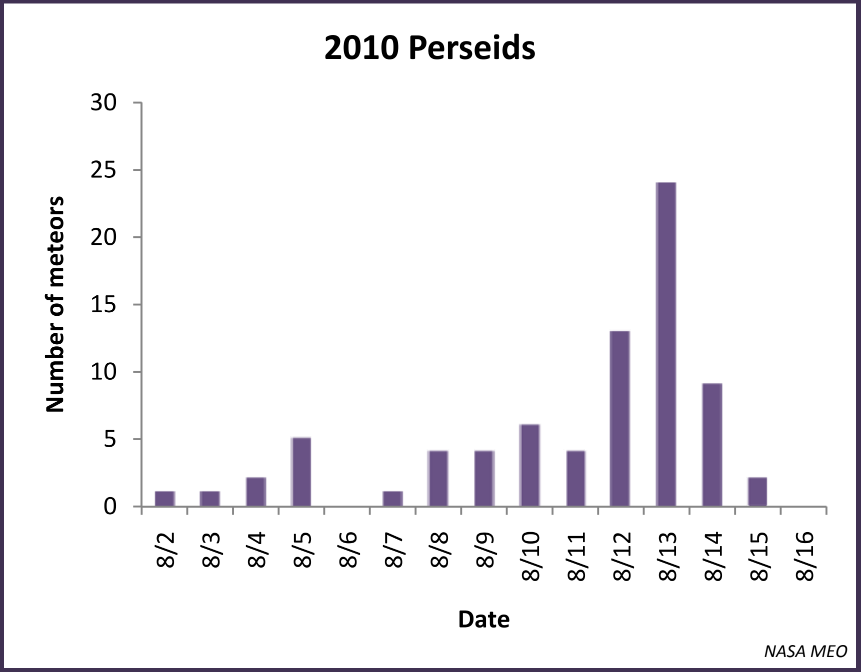
# Data Analysis – Date

- How many Perseids were seen in 2010? 76
- How many days were Perseids detected? 13
- Which day did we see the most number of Perseids? 8/13
- Which day did we see the least number of Perseids?

  8/6 and 8/16
- Why were no Perseids detected on some dates?

  Weather was cloudy

Students can use the table to create a histogram

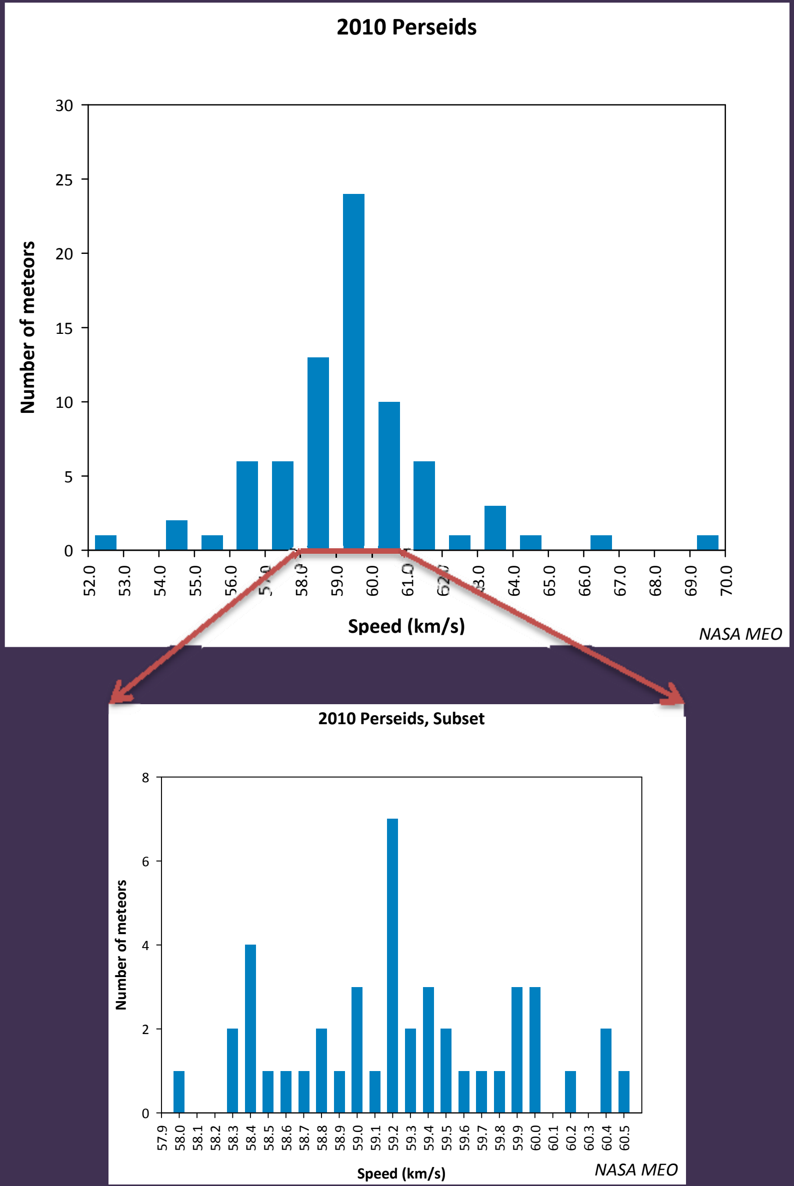


# Data Analysis – Speed

- What is the mean speed of the Perseids? 59.3 km/s
- What is the median of the speed distribution? 59.2 km/s
- What is the mode of the speed distribution? 59.2 km/s
- If a Perseid moving at 59.3 km/s traveled from New York City to Los Angeles, 3961 km, how long would it take to make the trip?

  66.8 seconds

Students can use the table to create a histogram



# Related Lesson: Speed, Velocity, Acceleration

- Definitions and examples of speed, velocity, acceleration
  - Speed = distance moved per unit of time
  - Velocity = speed, with a specified direction
  - Acceleration = rate of change of velocity


- What is information is on the Results Website, *http://fireballs.ndc.nasa.gov/,* speed or velocity?
  - Website gives data labeled as velocity, but no direction information is presented, so for all intents and purposes it is speed

- If the meteor were to be going 60 km/s when first detected, and 30 km/s 3 seconds later, what is its (average) acceleration?

# Data Analysis – Height

- At what height are most Perseids detected? 107-108 km

- What is the lowest detection height (beginning height)?

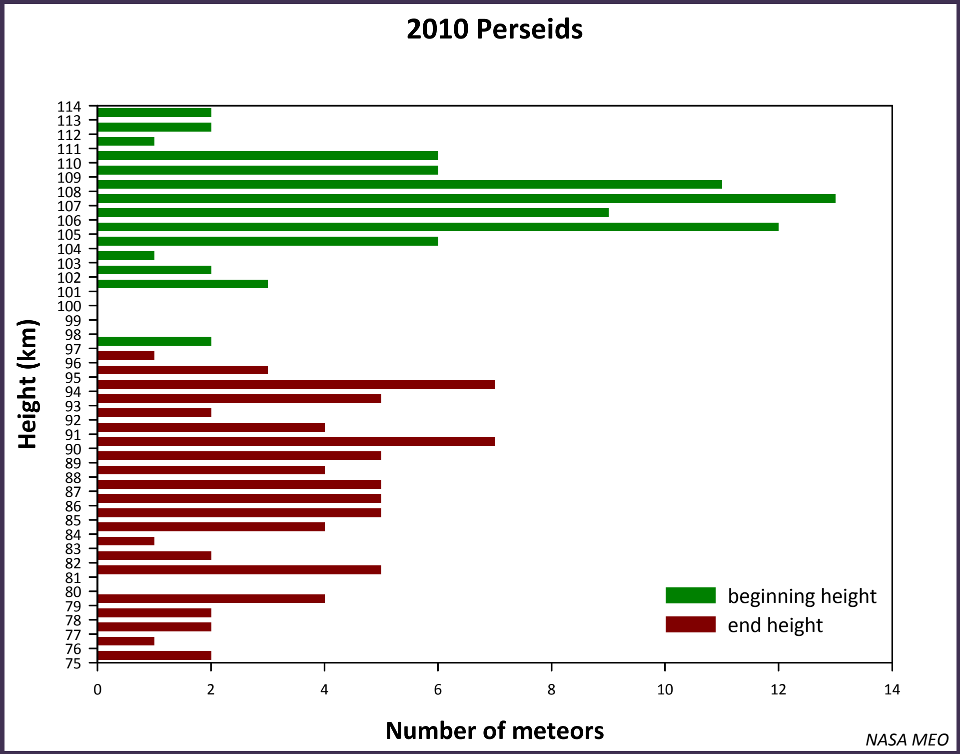
  97-98 km

- What is the lowest ablation height (end height)? 75-76 km

- Why is there such a large range of end heights?

  Larger mass particles penetrate deeper into the atmosphere than smaller particles

Similarly, students can create a histogram of heights



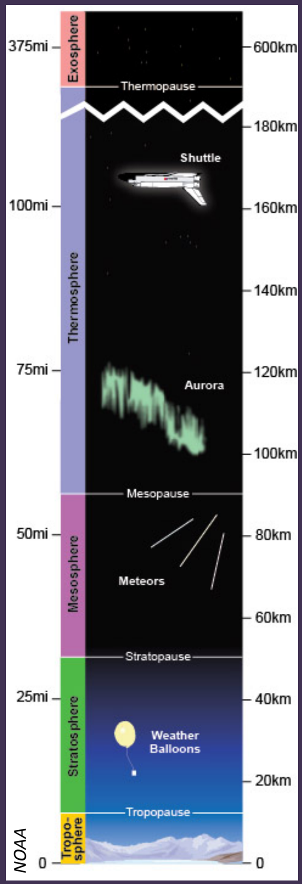

- In what layer of the atmosphere do most meteors burn up?

  Mesosphere or thermosphere

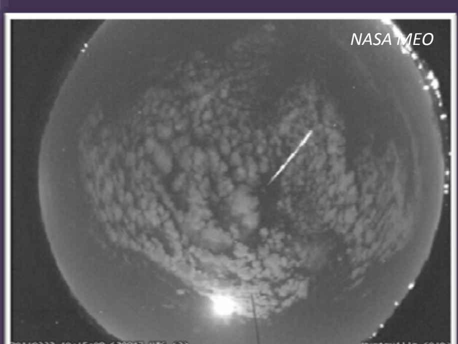
# Related Lesson: Atmosphere

- Which layer do meteors burn up?

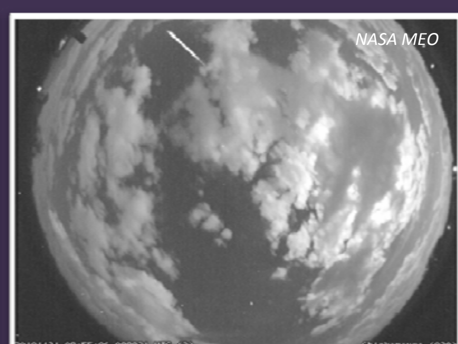
  (i.e. where are the molecules dense enough to start bumping into each other?)



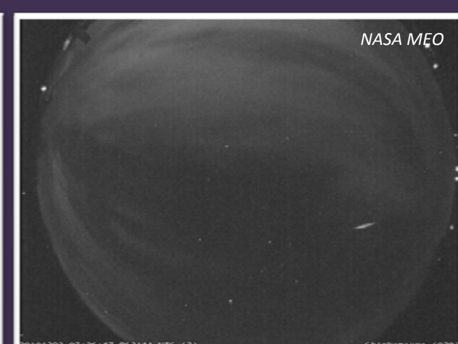

- Cloud types




Cirrocumulus



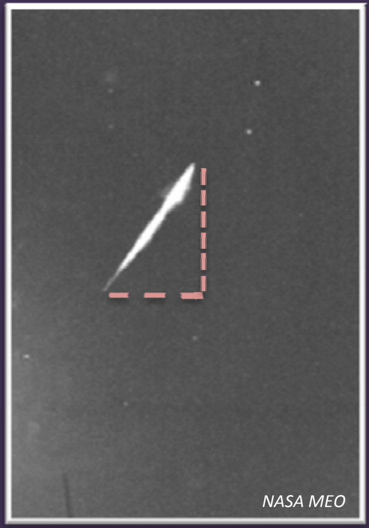

Altocumulus




Cirrus

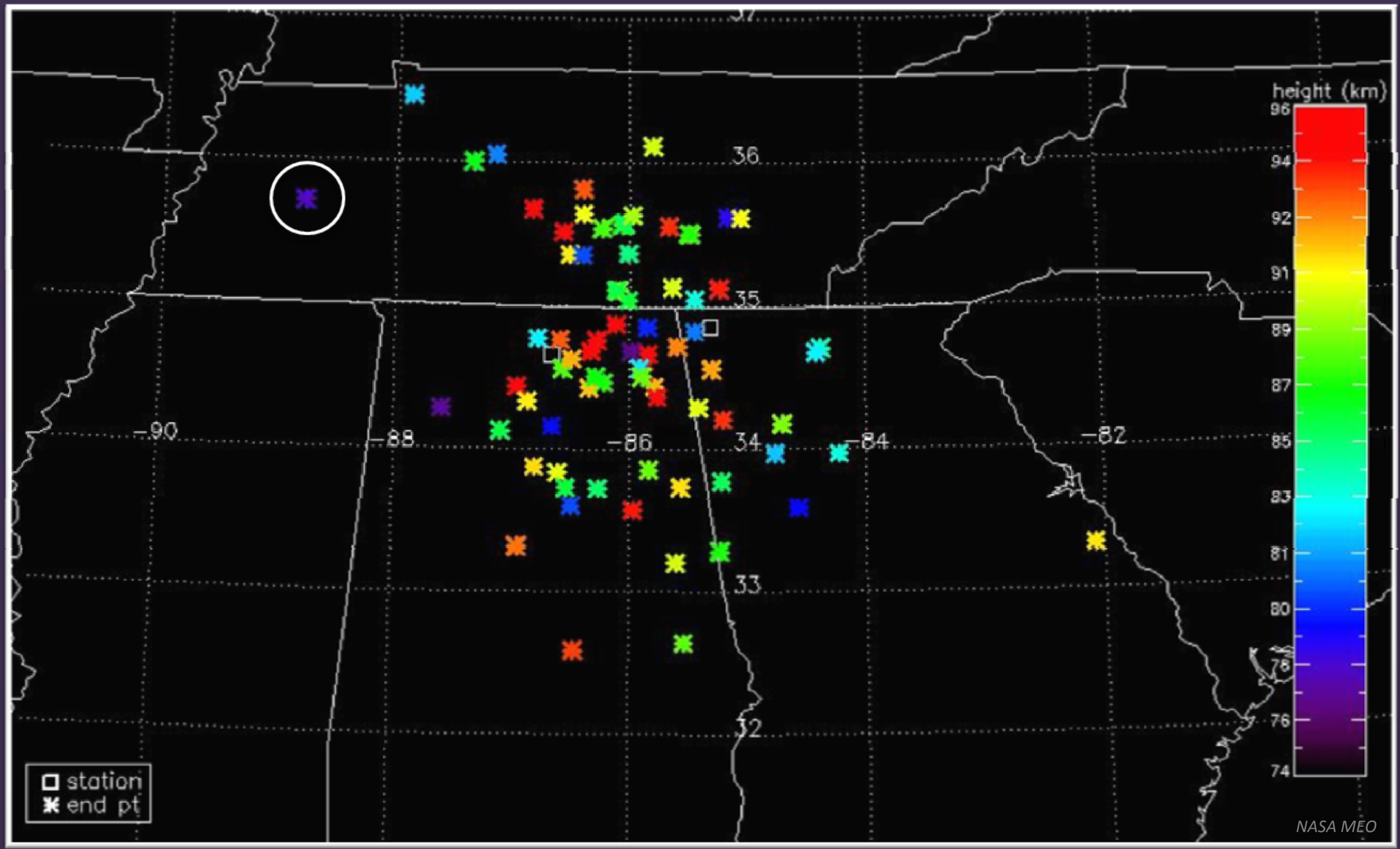
# Related Lesson: Energy

- Explain the relationship between potential and kinetic energy
  - Calculate the potential energy and kinetic energy of a 1 kg meteor at 50 km moving 59 km/s




- Energy transfer calculations

# Data Analysis – Location

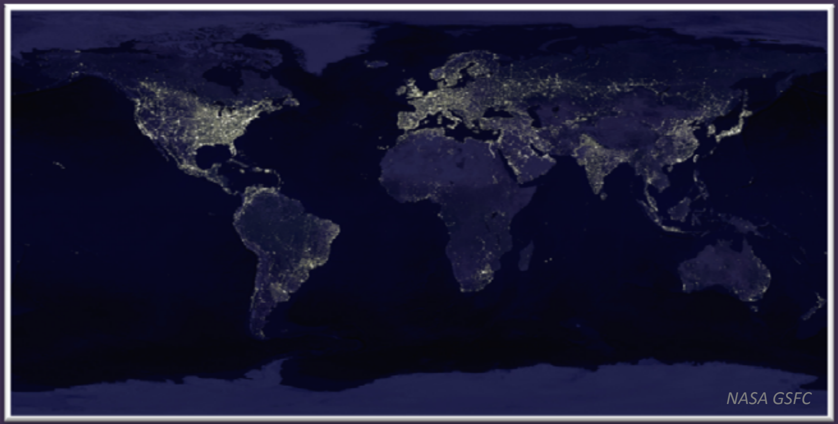



Students can plot meteor locations (those shown here are color coded by end height)

- In which state are the most meteors detected? Alabama
- How many meteors were seen south of latitude 33°N? 2
- Circle the meteor end point that was detected the farthest west.
- How many meteors with end heights ≤ 83 km were seen in Tennessee? 6

# Related Lesson:  Geography
## Latitude & Longitude

- What are latitude and longitude & how are they measured?
- Writing conventions
  - +34 40’50.12” versus 34.68059 N
  - -86 = 86 W = 274 E = +274
- Conversions

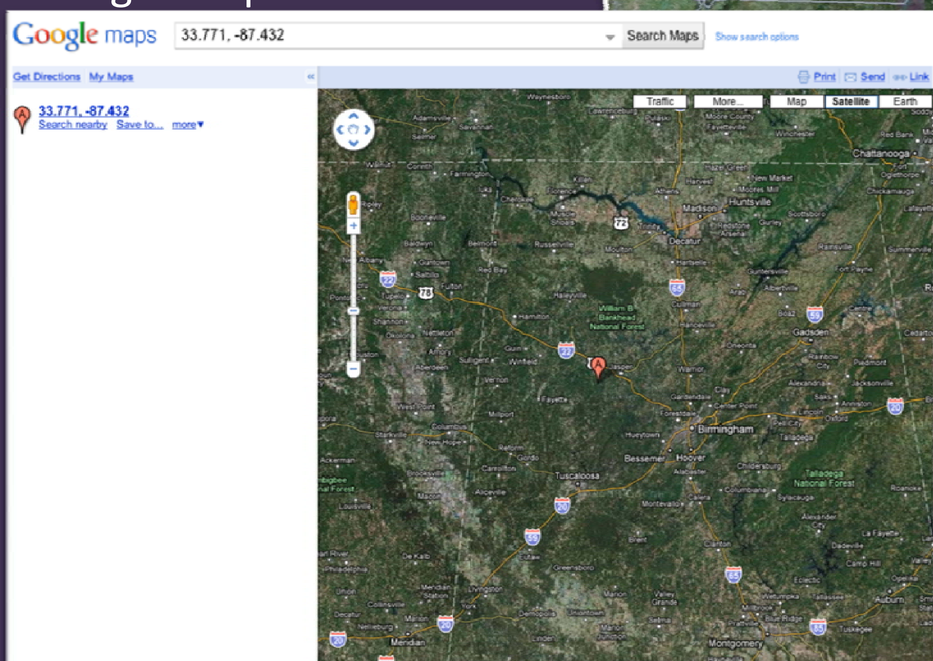


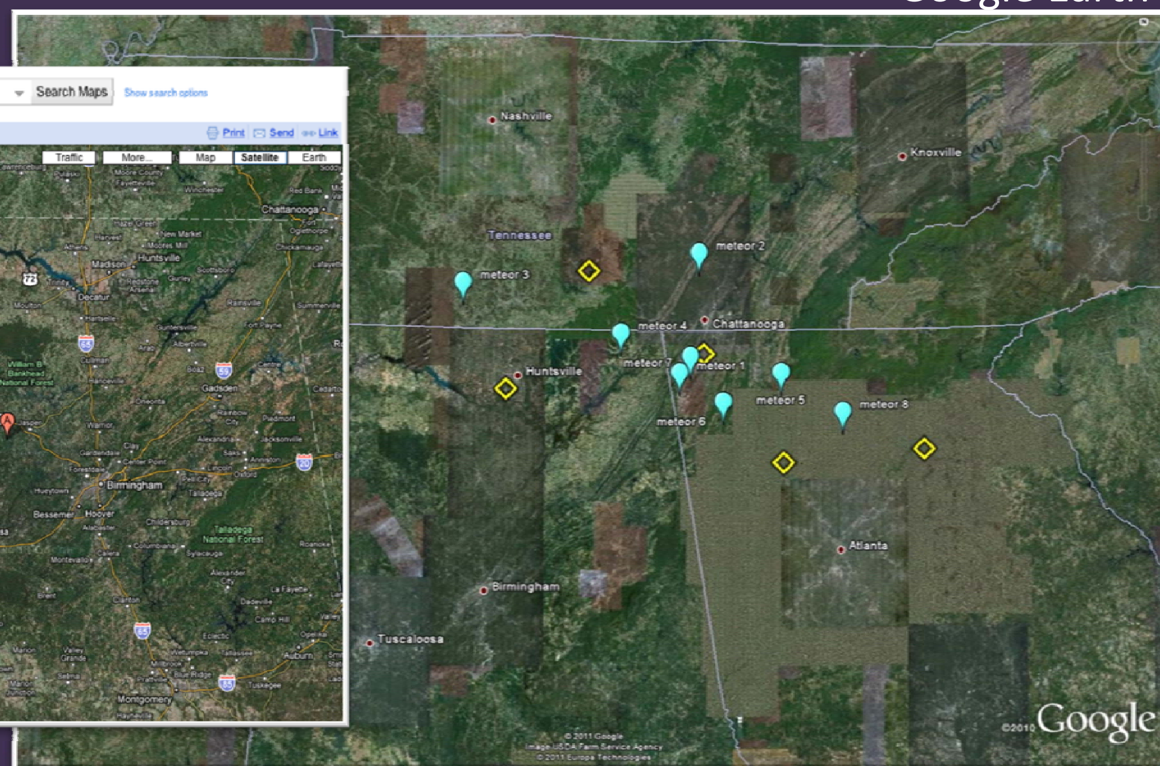
# Related Tools: Geography

- Plot meteor locations on Google Maps or Google Earth
  - http://maps.google.com/ & http://www.google.com/intl/en/earth/index.html
  - i.e. Latitude 33.771 N, Longitude -87.342 W
  - Can do this with all meteors associated with a shower, etc
  - Can plot the stations and the meteors together

Google Earth

Google Maps



# Data Analysis

Students can collect and record data themselves or work from a given table

- How many different showers are seen in this data? 4: CTA, NTA, ORI, and LEO
- Which shower's meteors are moving the fastest? LEO = Leonids
- How many events were Leonids? 8
- Which event is an Orionid meteor? 20091105 08:36:00
- How many events are likely to be satellites? 3 – those moving at 7 km/s

| date | time | speed (km/s) | source |
|---|---|---|---|
| 20091101 | 4:14:37 | 34.6 | |
| 20091101 | 10:00:37 | 57.9 | |
| 20091102 | 3:53:13 | 26.1 | |
| 20091102 | 4:25:54 | 42.7 | CTA |
| 20091102 | 7:02:53 | 68.3 | |
| 20091102 | 7:39:10 | 61.0 | |
| 20091102 | 10:46:21 | 61.8 | |
| 20091103 | 3:01:44 | 30.5 | NTA |
| 20091104 | 3:05:13 | 32.9 | NTA |
| 20091104 | 5:46:34 | 69.9 | |
| 20091104 | 7:05:07 | 62.9 | |
| 20091104 | 7:54:34 | 67.1 | |
| 20091104 | 9:48:47 | 60.6 | |
| 20091105 | 1:39:09 | 20.2 | |
| 20091105 | 1:51:52 | 22.3 | |
| 20091105 | 3:30:44 | 29.4 | NTA |
| 20091105 | 8:36:00 | 66.0 | ORI |
| 20091105 | 10:22:08 | 67.5 | |
| 20091105 | 10:30:07 | 68.4 | |
| 20091105 | 23:40:17 | 29.2 | |
| 20091106 | 7:31:24 | 64.5 | |
| 20091106 | 9:43:23 | 74.4 | |
| 20091106 | 9:55:46 | 50.6 | |
| 20091107 | 0:03:39 | 7.2 | |
| 20091107 | 0:04:22 | 7.6 | |
| 20091107 | 2:36:57 | 18.8 | |
| 20091107 | 8:24:26 | 65.9 | |
| 20091107 | 9:42:49 | 58.9 | |
| 20091107 | 10:42:49 | 65.0 | |
| 20091108 | 0:26:48 | 7.4 | |
| 20091108 | 3:23:36 | 40.1 | |
| 20091108 | 6:57:45 | 29.3 | NTA |
| 20091108 | 10:08:17 | 65.9 | |
| 20091108 | 11:23:11 | 65.8 | |
| 20091109 | 8:08:56 | 27.8 | |
| 20091112 | 4:16:52 | 23.6 | |
| 20091112 | 4:47:42 | 16.7 | |
| 20091112 | 6:35:43 | 34.7 | |
| 20091112 | 8:38:52 | 26.9 | NTA |
| 20091112 | 10:47:58 | 69.2 | |
| 20091113 | 0:47:05 | 15.9 | |
| 20091113 | 7:04:03 | 32.6 | NTA |
| 20091113 | 7:04:46 | 61.1 | |
| 20091113 | 7:58:10 | 24.1 | |

NASA MEO

| date | time | speed (km/s) | source |
|---|---|---|---|
| 20091113 | 8:32:09 | 72.5 | LEO |
| 20091113 | 10:21:29 | 67.7 | |
| 20091113 | 10:33:00 | 30.6 | NTA |
| 20091113 | 11:15:39 | 57.5 | LEO |
| 20091114 | 3:22:00 | 30.6 | NTA |
| 20091114 | 9:08:58 | 47.1 | |
| 20091114 | 10:22:56 | 29.0 | NTA |
| 20091114 | 10:27:23 | 64.8 | |
| 20091115 | 8:59:05 | 66.9 | |
| 20091115 | 9:48:32 | 69.4 | |
| 20091115 | 10:03:16 | 66.9 | |
| 20091115 | 10:16:33 | 43.8 | |
| 20091115 | 10:17:00 | 65.7 | LEO |
| 20091115 | 11:03:59 | 66.3 | LEO |
| 20091116 | 4:37:38 | 27.2 | NTA |
| 20091116 | 6:11:58 | 79.5 | LEO |
| 20091116 | 7:27:24 | 60.2 | |
| 20091116 | 7:37:23 | 69.6 | |
| 20091116 | 8:58:36 | 61.0 | |
| 20091116 | 9:33:07 | 59.5 | |
| 20091116 | 10:45:47 | 68.4 | LEO |
| 20091116 | 10:53:20 | 64.0 | LEO |
| 20091116 | 11:17:02 | 70.0 | LEO |
| 20091116 | 11:21:18 | 68.5 | |
| 20091120 | 8:11:42 | 71.1 | |
| 20091120 | 8:11:53 | 69.1 | |
| 20091120 | 8:51:34 | 66.5 | |
| 20091120 | 9:23:11 | 68.4 | |
| 20091120 | 9:36:12 | 70.2 | |
| 20091120 | 10:40:35 | 63.7 | |
| 20091120 | 11:18:26 | 56.4 | |
| 20091120 | 11:21:09 | 65.0 | |
| 20091121 | 10:02:36 | 33.9 | NTA |
| 20091121 | 23:33:37 | 13.1 | |
| 20091125 | 10:58:44 | 74.4 | |
| 20091126 | 0:44:42 | 28.7 | |
| 20091126 | 5:07:50 | 66.8 | |
| 20091126 | 6:41:33 | 61.9 | |
| 20091126 | 8:33:18 | 62.8 | |
| 20091127 | 5:47:53 | 24.1 | |
| 20091127 | 7:05:13 | 78.0 | |
| 20091127 | 10:03:56 | 68.3 | |
| 20091127 | 10:39:42 | 65.8 | |
| … | … | … | |

NASA MEO

# Related Lesson: International Space Station (ISS)

- The cameras sometimes detect ISS
- Lesson on the ISS
  - How it was built
  - Science performed there


- Educational tools at http://www.nasa.gov/audience/foreducators/index.html

# Related Tools: ISS Tracking Heaven's Above

Use 'Heavens Above' to determine times when ISS will be visible from your location
www.heavens-above.com

At front of site you can enter your position, in latitude and longitude.

## ISS - Visible Passes

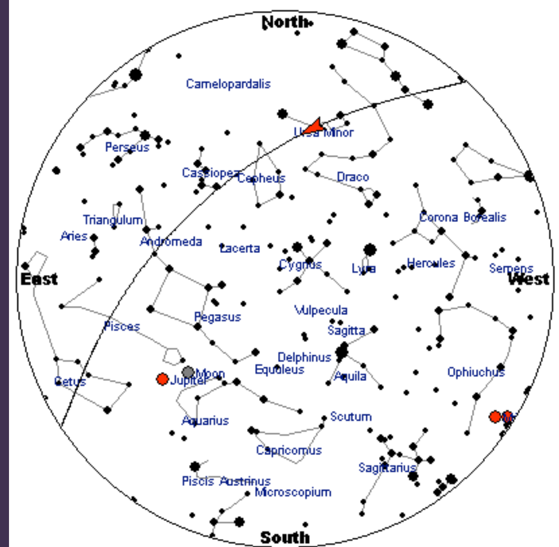
Search period start: 00:00 Friday, 12 November, 2010
Search period end: 00:00 Monday, 22 November, 2010
Observer's location: Huntsville, 34.7000°N, 86.6000°W
Local time zone: Central Standard Time (UTC - 6:00)
Orbit: 346 x 356 km, 51.6° (Epoch Nov 12)

Click on the date to get a star chart and other pass details.

| Date | Mag | Starts | | | Max. altitude | | | Ends | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Time | Alt. | Az. | Time | Alt. | Az. | Time | Alt. | Az. |
| 12 Nov | -1.6 | 17:28:35 | 10 | N | 17:30:24 | 15 | NNE | 17:31:11 | 14 | NE |
| 13 Nov | -3.3 | 17:53:44 | 10 | NW | 17:56:34 | 46 | NE | 17:56:53 | 43 | ENE |
| 14 Nov | -2.1 | 18:19:41 | 10 | WNW | 18:22:24 | 35 | SW | 18:22:54 | 32 | SSW |
| 15 Nov | -3.5 | 17:10:10 | 10 | NW | 17:13:03 | 53 | NE | 17:15:53 | 10 | ESE |
| 16 Nov | -1.6 | 17:36:08 | 10 | WNW | 17:38:45 | 31 | SW | 17:41:22 | 10 | SSE |
| 18 Nov | -1.1 | 16:52:23 | 10 | WNW | 16:54:56 | 27 | SW | 16:57:27 | 10 | SSE |

**Whole Sky Chart**

This chart shows the path of the satellite across the sky. Please note that East and West are **NOT** the "wrong way round" if you hold the chart over your head to correspond to the view of the sky.




**Pass Details**

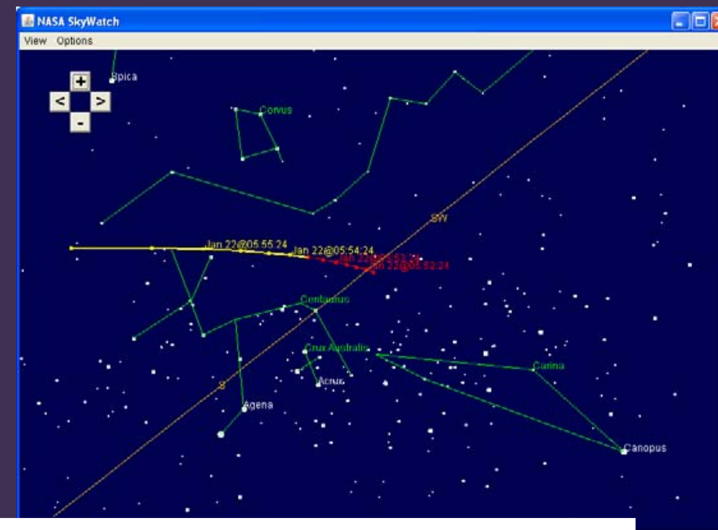
Date: Monday, 15 November, 2010
Satellite: ISS
Observer's Location: Huntsville ( 34.7000°N, 86.6000°W)
Local Time: Central Standard Time (GMT - 6:00)
Orbit: 346 x 356 km, 51.6° (Epoch 12 Nov)
Sun altitude at time of maximum pass altitude: -6.9°

| Event | Time | Altitude | Azimuth | Distance (km) |
|---|---|---|---|---|
| Rises above horizon | 17:08:08 | 0° | 316° (NW ) | 2,158 |
| Reaches 10° altitude | 17:10:11 | 10° | 322° (NW ) | 1,314 |
| Maximum altitude | 17:13:03 | 53° | 41° (NE ) | 437 |
| Enters shadow | 17:17:40 | 1° | 124° (SE ) | 2,033 |
| Drops below 10° altitude | 17:15:54 | 10° | 119° (ESE) | 1,302 |

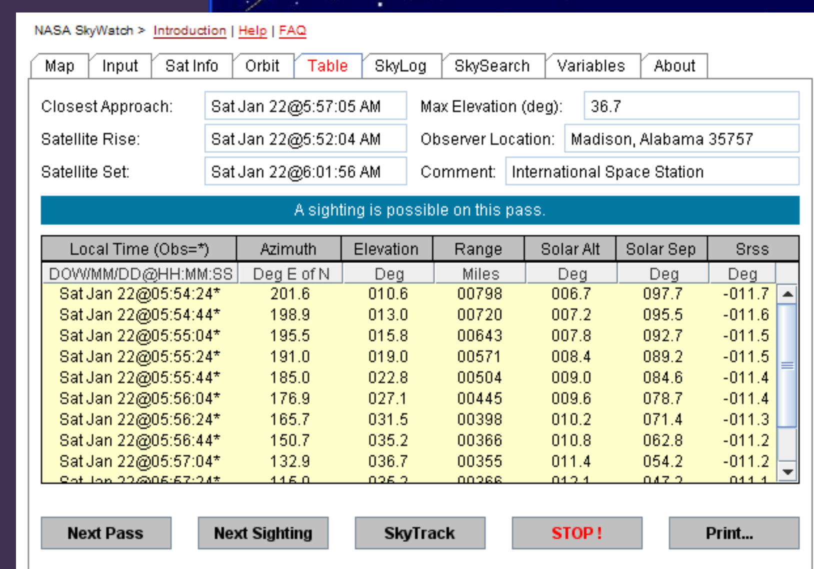
# Related Tools: ISS Tracking SkyWatch2.0

SkyWatch2.0 also determine times when ISS will be visible from your location http://spaceflight.nasa.gov/realdata/sightings/index.html

At front of site you can enter your position, using your zipcode.







# Related Lesson: Radiants and Constellations

- All meteors associated with one particular shower have similar orbits, and they all <u>appear</u> to come from the same place in the sky, called the *radiant*.

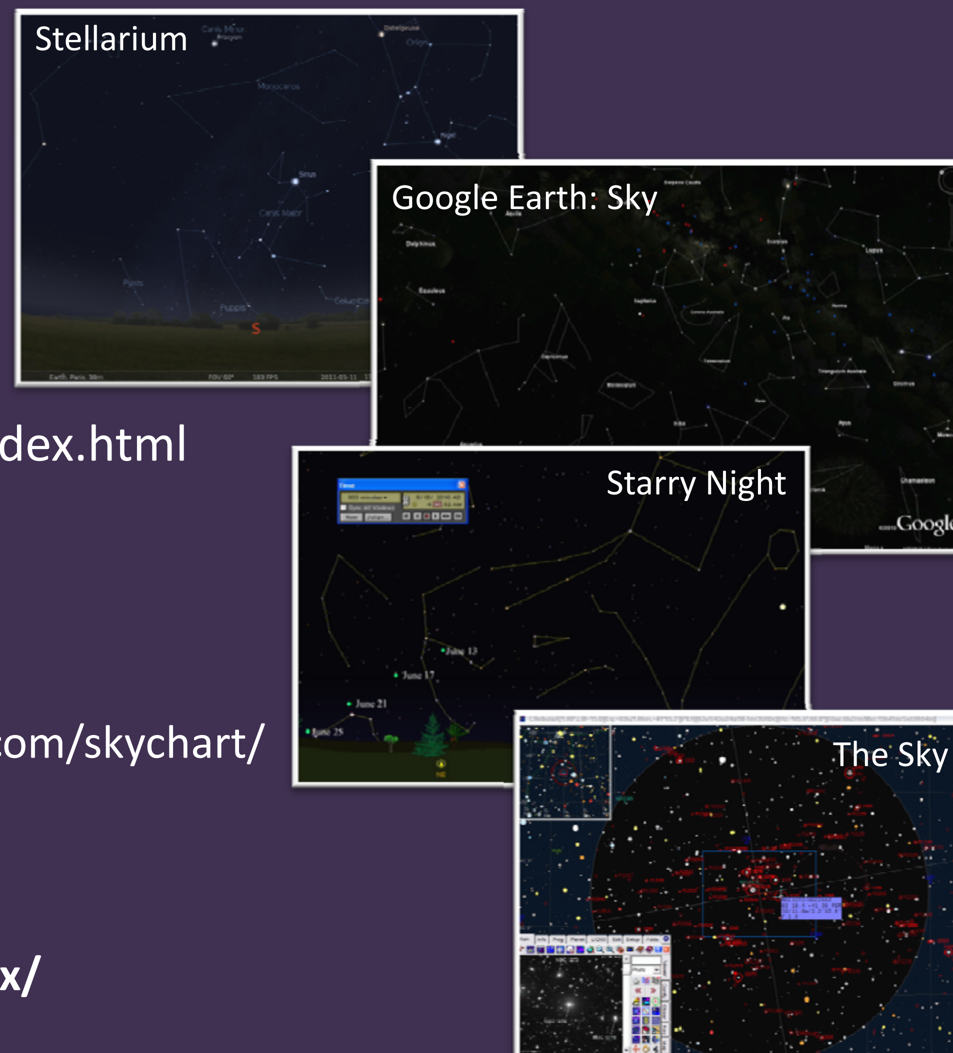
- The all-sky cameras can see stars and some constellations in addition to meteors.


Orionid meteor seen from 2 cameras

The radiant pt in Orion can be seen.


# Related Tools: The Night Sky

- Basic astronomy lessons in identifying main constellations (pole star, Orion's belt, etc)
- Stellarium
  - http://www.stellarium.org/
- Google Earth: Sky
  - http://earth.google.com/sky/index.html
- Starry Night
  - http://www.starrynight.com/
  - http://www.starrynighteducation.com/skychart/
- The Sky
  - www.bisque.com/products/**theskyx/**



# Data Analysis

Students can collect and record data themselves or work from a given table

- Besides satellites and shower meteors, what other meteor data is seen here?

Sporadic background meteor data (It is possible that events without identified sources are also shower meteors of some type.)

| date | time | speed (km/s) | source |
|---|---|---|---|
| 20091101 | 4:14:37 | 34.6 | |
| 20091101 | 10:00:37 | 57.9 | |
| 20091102 | 3:53:13 | 26.1 | |
| 20091102 | 4:25:54 | 42.7 | CTA |
| 20091102 | 7:02:53 | 68.3 | |
| 20091102 | 7:39:10 | 61.0 | |
| 20091102 | 10:46:21 | 61.8 | |
| 20091103 | 3:01:44 | 30.5 | NTA |
| 20091104 | 3:05:13 | 32.9 | NTA |
| 20091104 | 5:46:34 | 69.9 | |
| 20091104 | 7:05:07 | 62.9 | |
| 20091104 | 7:54:34 | 67.1 | |
| 20091104 | 9:48:47 | 60.6 | |
| 20091105 | 1:39:09 | 20.2 | |
| 20091105 | 1:51:52 | 22.3 | |
| 20091105 | 3:30:44 | 29.4 | NTA |
| 20091105 | 8:36:00 | 66.0 | ORI |
| 20091105 | 10:22:08 | 67.5 | |
| 20091105 | 10:30:07 | 68.4 | |
| 20091105 | 23:40:17 | 29.2 | |
| 20091106 | 7:31:24 | 64.5 | |
| 20091106 | 9:43:23 | 74.4 | |
| 20091106 | 9:55:46 | 50.6 | |
| 20091107 | 0:03:39 | 7.2 | |
| 20091107 | 0:04:22 | 7.6 | |
| 20091107 | 2:36:57 | 18.8 | |
| 20091107 | 8:24:26 | 65.9 | |
| 20091107 | 9:42:49 | 58.9 | |
| 20091107 | 10:42:49 | 65.0 | |
| 20091108 | 0:26:48 | 7.4 | |
| 20091108 | 3:23:36 | 40.1 | |
| 20091108 | 6:57:45 | 29.3 | NTA |
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| 20091113 | 7:04:03 | 32.6 | NTA |
| 20091113 | 7:04:46 | 61.1 | |
| 20091113 | 7:58:10 | 24.1 | |

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| date | time | speed (km/s) | source |
|---|---|---|---|
| 20091113 | 8:32:09 | 72.5 | LEO |
| 20091113 | 10:21:29 | 67.7 | |
| 20091113 | 10:33:00 | 30.6 | NTA |
| 20091113 | 11:15:39 | 57.5 | LEO |
| 20091114 | 3:22:00 | 30.6 | NTA |
| 20091114 | 9:08:58 | 47.1 | |
| 20091114 | 10:22:56 | 29.0 | NTA |
| 20091114 | 10:27:23 | 64.8 | |
| 20091115 | 8:59:05 | 66.9 | |
| 20091115 | 9:48:32 | 69.4 | |
| 20091115 | 10:03:16 | 66.9 | |
| 20091115 | 10:16:33 | 43.8 | |
| 20091115 | 10:17:00 | 65.7 | LEO |
| 20091115 | 11:03:59 | 66.3 | LEO |
| 20091116 | 4:37:38 | 27.2 | NTA |
| 20091116 | 6:11:58 | 79.5 | LEO |
| 20091116 | 7:27:24 | 60.2 | |
| 20091116 | 7:37:23 | 69.6 | |
| 20091116 | 8:58:36 | 61.0 | |
| 20091116 | 9:33:07 | 59.5 | |
| 20091116 | 10:45:47 | 68.4 | LEO |
| 20091116 | 10:53:20 | 64.0 | LEO |
| 20091116 | 11:17:02 | 70.0 | LEO |
| 20091116 | 11:21:18 | 68.5 | |
| 20091120 | 8:11:42 | 71.1 | |
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| 20091120 | 10:40:35 | 63.7 | |
| 20091120 | 11:18:26 | 56.4 | |
| 20091120 | 11:21:09 | 65.0 | |
| 20091121 | 10:02:36 | 33.9 | NTA |
| 20091121 | 23:33:37 | 13.1 | |
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| 20091126 | 8:33:18 | 62.8 | |
| 20091127 | 5:47:53 | 24.1 | |
| 20091127 | 7:05:13 | 78.0 | |
| 20091127 | 10:03:56 | 68.3 | |
| 20091127 | 10:39:42 | 65.8 | |
| … | … | … | |

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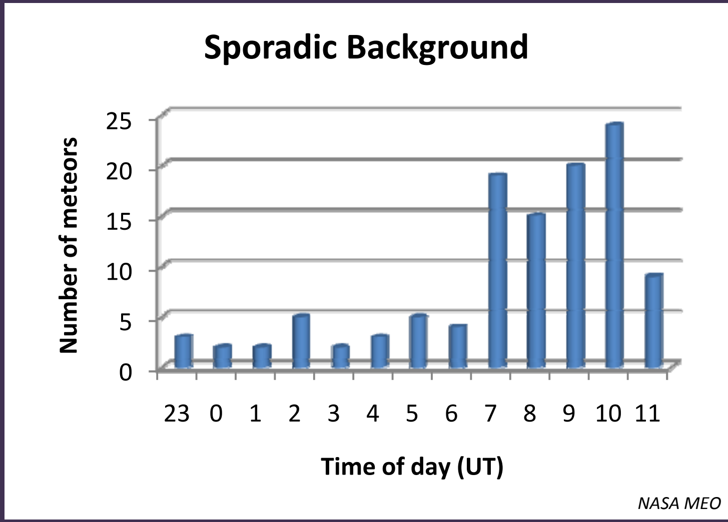
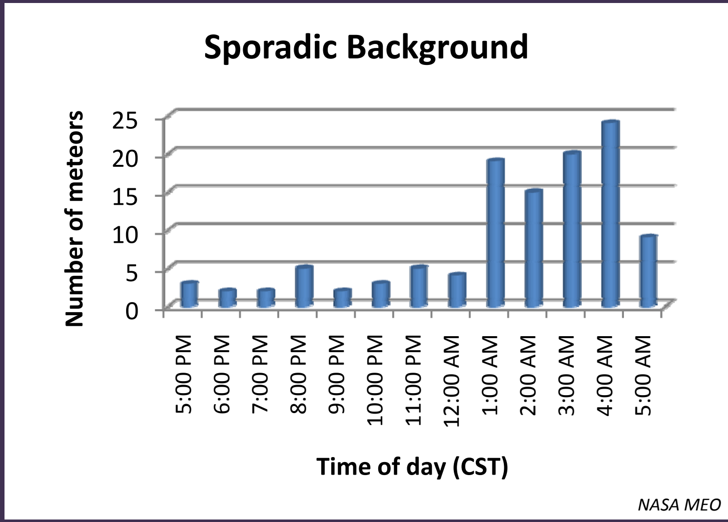
# Data Analysis – Time

- If it is 6 UT, what time is it in CST? 12:00 am CST
- During what time of day are the most meteors detected? 10 UT or 4:00 am CST
- What do you notice about the number of meteors seen before midnight compared to those seen after midnight? Less meteors are seen before midnight. More meteors are seen after midnight. More meteors are seen just before sunrise, in fact.
- Why do you think that is?

  The Earth travels (revolves) around its orbit around the Sun. It also rotates every 24 hours, creating night and day. More meteors are seen just before sunrise because at that time of day, the cameras are pointed in the direction that the Earth is moving in its orbit. So the Earth is running into meteoroids in space in the morning. In the evening, meteoroids have to be fast enough to catch up to the Earth – there aren't as many of those. This is similar to a car driving forwards – you get many bugs on the front windshield because you run into them. A bug would have to run into you in order to hit the back windshield. Can demonstrate with a globe and where we are on it.

Similarly, students can create a histogram of times



# Related Lesson:  Time Zones

- UT: Universal Time, or UTC: Coordinated Universal Time
  - (also known as Greenwich Mean Time GMT)
  - Standard time by which the world regulates clocks.
- Conversion between local time and UTC
- Standard time vs. daylight savings
- Why is it important to keep track of where you are when you see astronomical phenomenon?


| Pacific Standard Time | Mountain Standard Time | Central Standard Time | Eastern Standard Time | UT (Greenwich Mean Time) |
|---|---|---|---|---|
| 10:00 AM | 11:00 AM | 12:00 PM | 1:00 PM | 6:00 PM |

# Data Analysis – Orbits

- Which meteoroid traveled closest to the Sun? #4
- Which meteoroid orbit has the most uncertain semi-major axis? #2
- According to the table, which meteoroid orbit is most like a circle? Does the orbit diagram confirm this? #4, yes
- Based on the geocentric velocity, would you expect that these meteoroids are from the same source? Yes
- Based on the radiant coordinates, would you expect that these meteoroids are from the same source? Not necessarily – need error analysis

Students can collect and record data themselves or work from a given table

| orb elem | meteoroid 1 | meteoroid 2 | meteoroid 3 | meteoroid 4 |
|---|---|---|---|---|
| a | 6.621 ± 1.816 | 6.353 ± 5.067 | 5.202 ± 1.218 | 3.666 ± 2.014 |
| e | 0.855 ± 0.039 | 0.850 ± 0.118 | 0.814 ± 0.043 | 0.742 ± 0.140 |
| incl | 110.183 ± 0.560 | 112.238 ± 1.266 | 113.044 ± 0.579 | 112.036 ± 1.521 |
| omega | 151.816 ± 3.649 | 149.892 ± 2.995 | 154.492 ± 1.419 | 147.802 ± 4.505 |
| asc_node | 132.731 ± 0.000 | 137.539 ± 0.000 | 139.435 ± 0.000 | 140.304 ± 0.000 |
| v_g | 57.228 ± 0.497 | 57.854 ± 1.556 | 57.848 ± 0.540 | 56.678 ± 1.939 |
| v_h | 40.187 ± 0.457 | 40.133 ± 1.387 | 39.754 ± 0.502 | 38.848 ± 1.711 |
| alp_geo | 35.988 ± 2.103 | 43.849 ± 0.939 | 43.599 ± 0.659 | 47.476 ± 1.155 |
| del_geo | 57.010 ± 0.262 | 57.326 ± 0.496 | 56.982 ± 0.337 | 57.587 ± 0.431 |
| q_per | 0.959 ± 0.014 | 0.951 ± 0.009 | 0.969 ± 0.004 | 0.947 ± 0.012 |
| q_aph | 12.284 ± 3.629 | 11.756 ± 10.128 | 9.435 ± 2.434 | 6.386 ± 4.020 |

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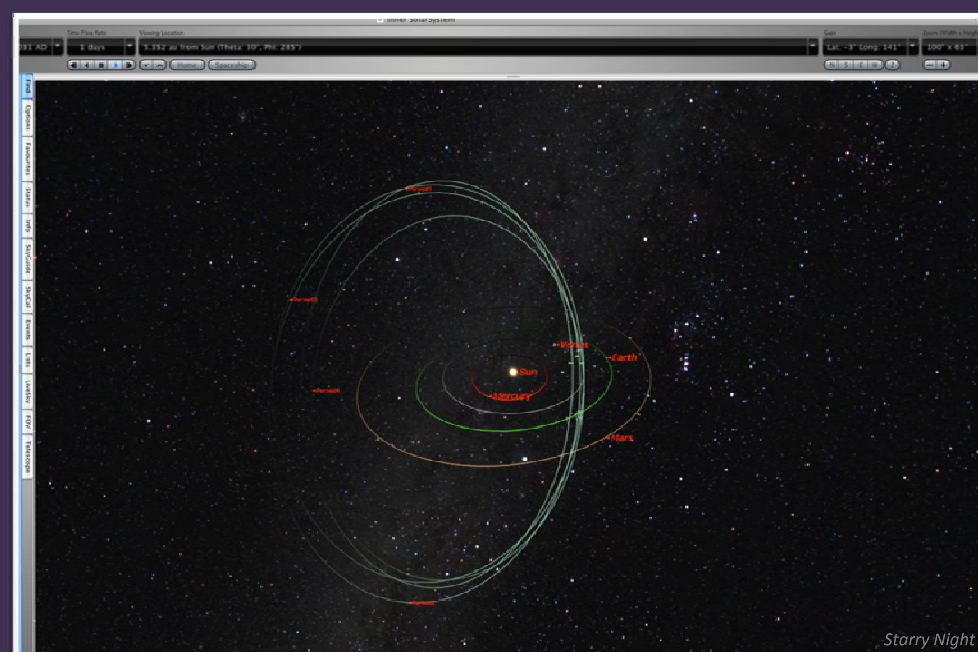


# Related Lesson: Orbits

- Discuss positions of meteoroids within Solar System and within Milky Way
- Explain the motion of objects in the day/night sky in terms of relative position
- What are orbital elements
- The orbits of these meteors can be plotted and compared to distances of planets, etc.
- Can find meteors that appear to be coming from the asteroid belt

# Related Tools:  Orbit Diagrams

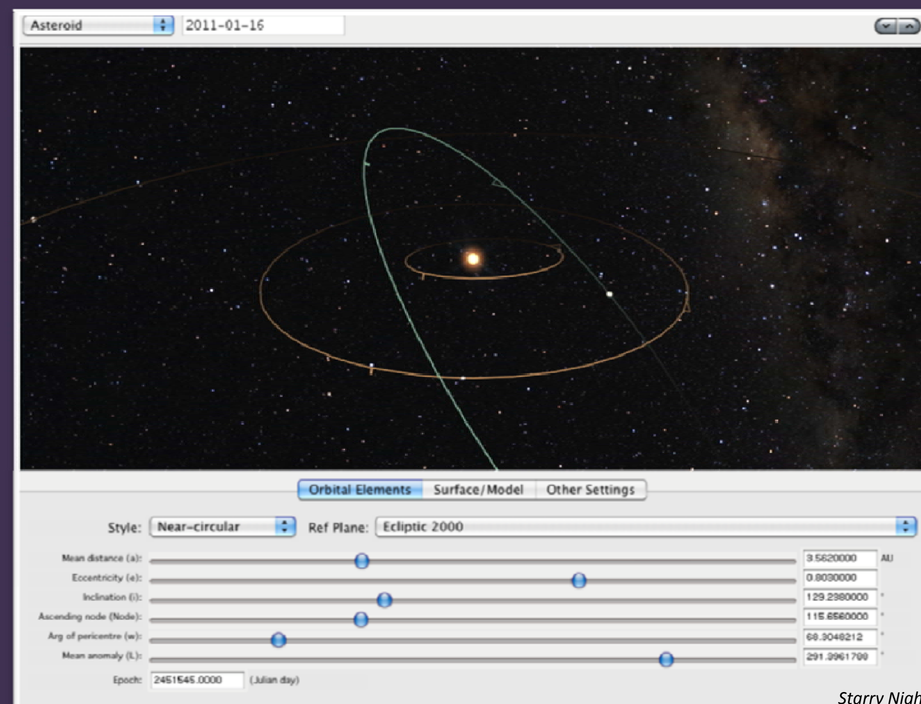
- Starry Night has a tool for visualizing orbits
  - File → add new asteroid orbiting the Sun
  - Enter orbital elements from Results Website

```
time 20110116 7.5278 hours
 lat  34 21 29.412 =  34.3582 deg
 lon 272 07 44.544 = 272.1290 deg
  ht 0.000 b -2.02353 0.11553 -8.17430 18.82434
      alp 173.635 +/-  3.143 deg
      del -24.549 +/-  0.588 deg
    v_inf  62.695 +/-  0.389 km/s
    v_avg  62.695 +/-  0.389 km/s

        a   3.562 +/-  1.405 AU
        e   0.802 +/-  0.087
     incl 129.238 +/-  3.367 deg
    omega  68.603 +/-  3.320 deg
 asc_node 115.656 +/-  0.000 deg
      v_g  61.496 +/-  0.396 km/s
      v_h  39.428 +/-  1.246 km/s
  alp_geo 173.494 +/-  3.187 deg
  del_geo -25.100 +/-  0.596 deg
    q_per   0.706 +/-  0.036 AU
    q_aph   6.418 +/-  2.840 AU
   lambda 184.900 +/-  2.893 deg
     beta -25.468 +/-  1.365 deg
true anom 291.396 +/-  1.365 deg

      T_j   0.8
       jd 2455577.81366
     slon 295.65650 deg
      sid 140.43898 deg
       Q*  13.830 deg
```

*NASA MEO*




*Starry Night*

# Related Lesson: Errors (Uncertainties)

- What IS error? What does error NOT imply?
  - Error does not mean ‘mistake’
  - Errors are unavoidable
    - No perfect equipment
- Why do we have errors?
  - In equipment
  - Depends on accuracy and precision of measurement
  - In calculations
- Fundamental question: Does the result agree with a theoretical prediction or results from other experiments?

```
time 20100813 10.1106 hours
 lat  36 03 02.771 =  36.0508 deg
 lon 272 51 06.552 = 272.8518 deg
  ht 0.000 b 9.45790 -1.84422 14.36964 -12.79559
       alp  49.612 +/-  2.901 deg
       del  55.246 +/-  2.425 deg
     v_inf  58.810 +/-  1.513 km/s
     v_avg  58.810 +/-  1.513 km/s

         a   3.496 +/-  1.898 AU
         e   0.732 +/-  0.144
      incl 115.702 +/-  3.510 deg
     omega 145.503 +/-  6.981 deg
  asc_node 140.421 +/-  0.000 deg
       v_g  57.651 +/-  1.542 km/s
       v_h  38.697 +/-  1.780 km/s
   alp_geo  49.117 +/-  2.950 deg
   del_geo  55.483 +/-  2.451 deg
     q_per   0.938 +/-  0.026 AU
     q_aph   6.055 +/-  3.789 AU
    lambda  62.919 +/-  2.178 deg
      beta  35.843 +/-  2.384 deg
true anom  34.496 +/-  2.384 deg
```

*NASA MEO*

# Related Lesson:  Errors - examples

Compare Perseid characteristics with known values from www.imo.net

- Radiant (direction which meteors appear to come from)
- Velocity

IMO: Perseid Velocity = 59 km/s

Perseid Radiant: alpha = 48º, delta = 58º

Three sample Perseids detected by the all-sky cameras:

```
time 20100812 9.5133 hours
 lat  34 45 30.925 =  34.7586 deg
 lon 273 43 23.748 = 273.7233 deg
  ht 0.000 b 9.45016 -1.83323 14.16553 -13.05955
      alp  47.316 +/-  1.505 deg
      del  60.723 +/-  1.216 deg
    v_inf  56.955 +/-  7.262 km/s
    v_avg  56.955 +/-  7.262 km/s

        a   5.433 +/- 16.941 AU
        e   0.827 +/-  0.535
     incl 106.667 +/-  5.827 deg
    omega 147.532 +/- 13.092 deg
 asc_node 139.436 +/-  0.000 deg
      v_g  55.751 +/-  7.407 km/s
      v_h  39.845 +/-  6.390 km/s
  alp_geo  46.923 +/-  1.548 deg
  del_geo  61.066 +/-  1.231 deg
    q_per   0.942 +/-  0.032 AU
    q_aph   9.924 +/- 33.852 AU
   lambda  63.974 +/-  1.106 deg
     beta  41.483 +/-  1.179 deg
true anom  32.467 +/-  1.179 deg
```

*NASA MEO*

```
time 20100814 7.1700 hours
 lat  34 20 01.103 =  34.3336 deg
 lon 273 08 00.688 = 273.1335 deg
  ht 0.000 b 9.47016 -1.82730 14.56924 -12.52790
      alp  43.577 +/-  4.597 deg
      del  54.170 +/-  0.502 deg
    v_inf  59.160 +/-  5.148 km/s
    v_avg  59.160 +/-  5.148 km/s

        a   3.227 +/-  4.226 AU
        e   0.695 +/-  0.396
     incl 116.790 +/-  3.725 deg
    omega 158.672 +/- 12.923 deg
 asc_node 141.263 +/-  0.000 deg
      v_g  57.895 +/-  5.243 km/s
      v_h  38.425 +/-  4.687 km/s
  alp_geo  43.821 +/-  4.690 deg
  del_geo  54.395 +/-  0.508 deg
    q_per   0.985 +/-  0.029 AU
    q_aph   5.468 +/-  8.440 AU
   lambda  58.934 +/-  3.152 deg
     beta  35.847 +/-  1.088 deg
true anom  21.328 +/-  1.088 deg
```

*NASA MEO*

```
time 20100813 10.1106 hours
 lat  36 03 02.771 =  36.0508 deg
 lon 272 51 06.552 = 272.8518 deg
  ht 0.000 b 9.45790 -1.84422 14.36964 -12.79559
      alp  49.612 +/-  2.901 deg
      del  55.246 +/-  2.425 deg
    v_inf  58.810 +/-  1.513 km/s
    v_avg  58.810 +/-  1.513 km/s

        a   3.496 +/-  1.898 AU
        e   0.732 +/-  0.144
     incl 115.702 +/-  3.510 deg
    omega 145.503 +/-  6.981 deg
 asc_node 140.421 +/-  0.000 deg
      v_g  57.651 +/-  1.542 km/s
      v_h  38.697 +/-  1.780 km/s
  alp_geo  49.117 +/-  2.950 deg
  del_geo  55.483 +/-  2.451 deg
    q_per   0.938 +/-  0.026 AU
    q_aph   6.055 +/-  3.789 AU
   lambda  62.919 +/-  2.178 deg
     beta  35.843 +/-  2.384 deg
true anom  34.496 +/-  2.384 deg
```

*NASA MEO*

# General Project Ideas

- Complete study of a specific meteor shower
  - When it was first documented
  - Characteristics of it (velocity, radiant, meteor rates)
- Compare and contrast different meteor showers
  - Studying individual showers to try to find similarities between shower meteors
- Study the different characteristics between shower meteors and sporadic background meteors
- Explore the world of comets, asteroids, meteoroids
  - Differences in composition, differences in orbit, differences in size
  - Where they originate
  - Why NASA is interested in studying them
- Meteors throughout history and how they were interpreted
- The meaning of meteors in song and literature (http://www.imo.net/projects/beliefs)

# Other resources

Print

- Martin Beech: *Meteors and Meteorites*
- Robert Lunsford: *Meteors and How to Observe Them*
- IMO Visual Observers Handbook
- M. Seeds and D. Backman: *Horizons: Exploring the Universe*

Online

- Meteor Observations: *http://www.imo.net*
- Meteor Info & Fireball FAQs: *http://amsmeteors.org*
- Comets: *http://epoxi.umd.edu/4education/index.shtml*
- Meteoroid Environment Office: *http://meo.nasa.gov*
- Watch the Skies! *http://www.nasa.gov/topics/solarsystem/features/watchtheskies/*
- Solar System Exploration: *http://solarsystem.nasa.gov/planets/index.cfm*

# Citations


- Halliday, I. (1971), Photographic Fireball Networks. In C. L. Hemenway (Ed.), *Evolutionary and Physical Properties of Meteoroids,* NASA SP-319, 1-8.
- M. Seeds, & Backman, D. (2009). *Horizons: Exploring the Universe, 11th Edition.* Brooks Cole Publishing
- McKinley, D.W.R. (1961). *Meteor Science and Engineering*. New York, NY: McGraw-Hill Book Company Inc.
- Ceplecha, Z., Borovicka, J., Elford, G.W., Revelle, D.O., Hawkes, R.L., Porubcan, V., & Simek, M., (1998). Meteor Phenomena and Bodies. *Space Science Reviews, 34,* 327-471

# End

Results Website: *http://fireballs.ndc.nasa.gov/*

Workshop Material:
*http://www.nasa.gov/offices/meo/outreach/all_sky_fireball_network_detail.html*

Questions:

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